NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

TOWN OF CREIGHTON, SASKATCHEWAN

APM-REP-06144-0054

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PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT

LINEAMENT INTERPRETATION

TOWN OF CREIGHTON, SASKATCHEWAN

NWMO REPORT NUMBER:
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EXECUTIVE SUMMARY

In December 2011, Creighton, Saskatchewan, expressed interest in continuing to learn more about the Nuclear Waste Management Organization's nine-step site selection process, and requested that a preliminary assessment be conducted to assess potential suitability of the Creighton area for safely hosting a deep geological repository (Step 3). This request followed the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary desktop study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Creighton area contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a lineament investigation assessment completed as part of the desktop geoscientific preliminary assessment of the Creighton area (Golder, 2013). The lineament assessment focussed on identifying surficial and geophysical lineaments and their attributes using publically available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the Creighton area in east-central Saskatchewan. The assessment of interpreted lineaments in the context of identifying siting areas that have the potential to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (Golder, 2013).

The lineament investigation interprets the location and orientation of potential bedrock structural features (e.g., individual fractures or fracture zones) within the context of the local and regional geological setting. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were interpreted from multiple, publically-available datasets (aeromagnetic, electromagnetic, CDED, SRTM, SPOT and LandSAT);
- Lineament interpretations were made by documented specialist observers and using a standardized workflow;

- Lineament interpretations were analyzed based on an evaluation of the quality and limitations of the available datasets;
- Interpreted lineaments were separated into two categories (brittle and ductile) based on their character expressed in the aeromagnetic data.
- Lineament interpretations were analyzed using reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different datasets, relative ages and/or documentation in literature; and
- Final classification of the lineament interpretation was done based on length and reproducibility.

The distribution of lineaments in the Creighton area reflects the bedrock structure, resolution of the datasets used, and surficial cover. It should be noted that, in accord with our understanding of the bedrock geology of the Creighton area, no dyke lineaments were identified during the course of this study. Surface lineament density, as demonstrated in this study, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the northeastern part of the Creighton area where the thickness and extent of surficial cover is relatively low. The lowest density of lineaments was observed in the southwest and over low lying areas covered by overburden and wetlands. On the basis of the structural history of the Creighton area, a framework was also developed to constrain the relative age relationships of the interpreted lineaments.

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1 INTRODUCTION

In December 2011, the Town of Creighton, Saskatchewan expressed interest in continuing to learn more about the Nuclear Waste Management Organization's (NWMO) nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess potential suitability of the Creighton area for safely hosting a deep geological repository (Step 3).

The overall preliminary assessment of potential suitability is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability; engineering; transportation; environment and safety; as well as social, economic and cultural considerations (NWMO, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Creighton area contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a lineament investigation study completed as part of the desktop geoscientific preliminary assessment of the Creighton area (Golder, 2013). The lineament study focussed on identifying surficial and geophysical lineaments and their attributes using publicly-available digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets for the Creighton area in east-central Saskatchewan. The assessment of interpreted lineaments in the context of identifying siting areas that are potentially suitable for hosting a repository is provided in the desktop preliminary geoscientific assessment report (Golder, 2013). The lineament study focused on Creighton and its periphery, referred to as the "Creighton area" in this report.

1.1 SCOPE OF WORK

The scope of work for this study includes the completion of a lineament interpretation of remotely-sensed datasets, including surficial (digital elevation data and satellite imagery) and geophysical (aeromagnetic) datasets for the Creighton area (approximately 660 km^2) in east-central Saskatchewan (Figure 1). The lineament investigation interprets the location and orientation of potential bedrock structural features (e.g., individual fractures or fracture zones) and helps to evaluate their relative timing relationships within the context of the local and regional geological setting. For the purpose of this report, a lineament is defined as, 'an extensive linear or arcuate geologic or topographic feature'. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were mapped from multiple, readily-available datasets that include satellite imagery (Système Pour l'Observation de la Terre, SPOT), digital elevation models (Canadian Digital Elevation Data, CDED; and Shuttle Radar Topography Mission, SRTM), and aeromagnetic geophysical survey data;
- Lineament interpretations from each source data type were made by two documented specialist observers for each dataset (e.g., geologist, geophysicist). Ductile lineaments were interpreted from the aeromagnetic geophysical survey dataset by an automated picking routine with confirmation by a single documented specialist observer;
- Lineaments were analyzed based on an evaluation of the quality and limitations of the available datasets, age relationships, reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different datasets, and/or documentation in literature; and
- Classification of lineaments was done based on length and reproducibility.

These elements address the issues of subjectivity and reproducibility normally associated with lineament investigations, and their incorporation into the methodology increases the confidence in the resulting lineament interpretation.

At this desktop stage, a classification scheme was used to separate the interpreted features into general categories based on their observed character in the Creighton area. These categories include ductile lineaments and brittle lineaments. Expert judgment and understanding of the bedrock geology of the Creighton area provided the basis for this categorization. Consistent with the known bedrock geology of the Creighton area, no dyke lineaments were interpreted during this study. The two categories employed in the analysis are described briefly below:

- **Ductile lineaments**: Features which were interpreted as being associated with the internal fabric of the rock units (including sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation) were classified as ductile lineaments. This category also includes recognizable penetrative shear zone fabric.
- **Brittle lineaments**: Features interpreted as fractures (joints or joint sets, faults or fault zones, and veins or vein sets), including those that offset the continuity of the ductile fabric described above, were classified as brittle lineaments. This category also includes

brittle-ductile shear zones, and brittle partings interpreted to represent discontinuous re-activation parallel to the ductile fabric. At the desktop stage of the investigation, this category also includes features of unknown affinity.

The desktop interpretation of remotely-sensed datasets necessarily includes a component of uncertainty as a result of data quality, scale of the area, expert judgement, and to a certain extent, the quality of the pre-existing knowledge of the bedrock geology of the Creighton area. Therefore the ductile or brittle categorization of each identified feature, as described herein, is preliminary, and would need to be confirmed during future stages of the site evaluation process, should the community be chosen by the NWMO and remain interested in continuing with the site selection process.

1.2 QUALIFICATIONS OF THE INTERPRETATION TEAM

The project team employed in the lineament interpretation component of the Phase 1 Desktop Geoscientific Preliminary Assessment consists of qualified experts from J.D. Mollard and Associates (2010) Limited, Regina (JDMA), Golder Associates Ltd., Mississauga, and Patterson, Grant and Watson Limited, Toronto (PGW). JDMA coordinated the lineament study with the support of PGW who conducted the lineament interpretation on the geophysical data.

Following is a brief description of the qualifications of project team members.

Lynden Penner, M.Sc., P.Eng., P.Geo. has undertaken the advancement of lineament research through the application of aerial and satellite imagery, DEMs, and GIS technology for a variety of projects including oil and gas exploration, potash mine development, groundwater exploration and contamination, CO2 sequestration studies, and assessing gas leakage from oil and gas wells beginning in 1986 and continuing to present. Given his expertise in mapping and understanding lineaments, Mr. Penner advised project team members on lineament mapping approaches and assisted with mapping lineaments from remotely sensed imagery and worked with the project team to evaluate the significance of the mapped, coincident and linked lineaments.

Dr. Jason Cosford, Ph.D., P.Geo. has contributed to a wide range of terrain analysis studies conducted by JDMA, including routing studies (road, rail, pipeline, and transmission line), groundwater exploration, granular resource mapping, and environmental sensitivity analyses. Dr. Cosford, Mr. Penner and Dr. Jack Mollard were responsible for shallow groundwater studies for the Weyburn CO2 sequestration research project. Dr. Cosford provided interpretation of the surficial lineaments and coordinated the evaluation of lineament attributes, and oversaw the preparation of integrated lineament datasets.

Shayne MacDonald, B.Sc., is an experienced GIS technician and remote sensing specialist. He provided GIS and image processing support for these studies and assisted with developing integrated lineament datasets under the direction of Dr. Cosford.

Jessica O`Donnell, M.Sc., is an experienced GIS technician and remote sensing specialist. She provided GIS and image processing support for these studies and assisted with developing integrated lineament datasets under the direction of Dr. Cosford.

Dr. Alex Man, Ph.D., P.Eng. is a senior geological engineer with a diverse background tailored towards the management of nuclear waste in deep geological repositories. He has conducted research on engineered clay barriers for high-level nuclear waste isolation on behalf of NWMO. Dr. Man was responsible for managing a geotechnical laboratory and conducting large-scale demonstration tests in both laboratory and underground environments while at AECL's Underground Research Laboratory. His field experience includes the drilling of boreholes to depths up to 1,200 m, in situ stress measurements, core orientation (for fracture mapping), hydrogeologic (packer) testing, and installation of hydrogeological monitoring systems for the purpose of site characterization for nuclear waste management. In addition, Dr. Man has 18 years of experience in the consulting field, where he conducted numerous geological and hydrogeological site investigations across Canada. In this study, Dr. Man was the second interpreter of the surficial lineaments.

Dr. James Misener, Ph.D., P.Eng. is President of PGW and a senior geophysicist with 37 years of experience in all aspects of geophysics and geophysics software applications. Dr. Misener founded Geosoft Inc. and led its development of world-leading geosciences software applications until he succeeded Dr. Paterson as President of PGW. He has directed implementation of geophysical data processing systems; initiated and managed major continental scale compilations of aeromagnetic/marine magnetic data in North America and worldwide including interpretation of aeromagnetic, radiometric, gravity and electromagnetic surveys in: Algeria, Brazil, Cameroon, Niger, Ivory Coast, Zimbabwe, Malawi, Kenya, China, Suriname, and Ireland. Dr. Misener provided interpretations of geophysical survey data, and provided interpretation of geophysical lineaments.

Stephen Reford, B.A.Sc., P.Eng. is a senior consulting geophysicist and Vice-President of PGW. Mr. Reford has more than 30 years of experience in project management, acquisition and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data throughout and gamma-ray spectrometer surveys for clients throughout Canada and around the world. Projects include management of the geophysical component of Operation Treasure Hunt for the Ontario Ministry of Northern Development and Mines as well as a similar role for the Far North Geoscience Mapping Initiative (2006-2009). Mr. Reford has served as a consultant to the International Atomic Energy Agency (IAEA) in gamma-ray spectrometry and is co-author of two books on radioelement mapping. Mr. Reford coordinated the interpretation of geophysical data, and was the second interpreter of the geophysical lineaments.

1.3 REPORT ORGANIZATION

Section 2.0 describes the setting of the Creighton area, which includes subsections on physical geography, bedrock geology, geological and structural history, Quaternary geology, and land use. Section 3.0 provides information on the source data and explains the methodology used to identify and assess lineaments. Section 4.0 presents the findings of the lineament interpretation with a description of lineaments by each dataset and a description and classification of integrated lineaments. Section 5.0 offers a discussion of the findings, specifically the lineament density, reproducibility and coincidence, lineament length, fault and lineament relationships, and relative age relationships. Section 6.0 is a summary of the report.

The primary source for all of the background information presented herein is the main report written by Golder (2013). This report also draws upon information from the supporting reports on terrain analysis (JDMA, 2013) and geophysics (PGW, 2013).

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

A detailed discussion of the geological setting of the Creighton area is provided in a separate report (Golder, 2013). The following sections on physical geography, bedrock geology, structural history, Quaternary geology and land use, present summaries of the information presented in Golder (2013), JDMA (2013) and PGW (2013) where applicable, in order to provide the necessary context for discussion of the results of this lineament study (Section 5.0).

2.1 PHYSICAL GEOGRAPHY

A detailed discussion of the physical geography of the Creighton area is provided in a separate terrain analysis report by JDMA (2013). The Creighton area is located at the southern margin of the Precambrian Shield. Local relief is generally low with variations in elevation of less than 100 m. Ground surface elevation ranges from about 292 m at the shore of Schist Lake in the southeast to about 369 m in the north, immediately south of Ahrens Lake. The major gradients are from the north into Amisk Lake and into Schist Lake.

The large lakes and the rugged terrain bordering them probably represent the most distinct topographic features in the area, especially in light of the relatively flat-lying terrain in between. Amisk Lake and the highly irregular terrain around its margins forms the main topographic feature in the southwestern part of the area.

The next most distinct topographic features in the Creighton area are the elevated, plateau-like surfaces, which largely represent the surface expression of plutons (Figure 4 in JDMA, 2013). The east-west trending ridge north of Johnson Lake is probably the best example. The isolated summits on this generally flat-topped, 5 to 8 km wide feature are at elevations of 360 to 370 masl, which are generally 30 m above the lakes on either side of the ridge. The elevated aspect of these plateau-like intrusive bodies is generally provided by the inset nature of the shear zones and belts of metasedimentary and metavolcanic rocks around their margins. Generally, the greatest relief associated with these features occurs in a band around their margins.

The Creighton area contains some large lakes, including Amisk Lake, which is 308 km^2 in extent, of which about 41 km^2 falls within the Creighton area. Annabel Lake (12 km^2) and Johnson Lake (7 km^2) are the only other lakes larger than 5 km^2. Schist Lake is a large lake (24 km^2), but only a small part of it is within the Creighton area. There is a high density of small lakes on the Reynard Lake pluton in an area northwest of Highway 167. Surface water covers approximately 16% of the Creighton area. The surficial hydrology exhibits drainage patterns (e.g., orientation, alignment, and shoreline morphology) that closely follow bedrock structures. Surface drainage patterns mark the location of several large shear zones, such as Annabel Lake shear zone, West Arm shear zone, Mosher Lake shear zone, and Comeback Bay shear zone (discussed further below).

2.2 GEOLOGICAL SETTING

The Canadian Shield is the tectonically stable core of the North American continent created from a collage of ancient (Archean) cratons and accreted juvenile arc terrains that were progressively amalgamated over a period of more than 2 billion years (Ga) during the Proterozoic Eon. Among the major orogenies that contributed to the assembly of the Canadian Shield is the Trans-Hudson Orogeny, which resulted from the closure of the Manikewan Ocean and terminal collision of the Rae-Hearne, Superior and Sask Cratons approximately 1.9 to 1.8 Ga. The resulting Trans-Hudson Orogen extends from South Dakota through Hudson Bay into Greenland and Labrador. Within Canada, the Trans-Hudson Orogen is a region approximately 500 km wide located between the Superior Craton to the southeast and the Rae-Hearne Craton to the north and northwest (Corrigan et al., 2007).

The Creighton area is located in the Flin Flon domain, which is part of the Reindeer zone of the Trans-Hudson Orogen that comprises part of the Canadian Shield in northern Saskatchewan. The area is immediately north of the contact with the Western Canada Sedimentary Basin, which is the Phanerozoic cover over the southern part of the province. Figure 2 depicts the regional tectonic setting.

The Reindeer zone consists of a collage of Paleoproterozoic arc and oceanic volcanic rocks, plutons, and younger molasse and turbiditic sedimentary rocks (NATMAP, 1998; SGS, 2003). Most of these rocks were formed in an oceanic to transitional subduction-related arc setting. During collision of the Sask craton with the Rae-Hearne craton these Reindeer zone rocks were thrust over the Sask craton along the Pelican thrust (Corrigan et al., 2005; Morelli, 2009). The Reindeer zone structurally overlies the approximately 3.2 to 2.4 Ga Archean metaplutonic and paragneissic rocks of the Sask craton, which are exposed in the western portion of the Flin Flon domain through the Pelican window, located approximately 70 to 80 km to the west of the Town of Creighton (Lucas et al., 1999; Ashton et al., 2005).

The Flin Flon-Glennie complex occurs within the southeastern portion of the Reindeer zone in Saskatchewan (SGS, 2003; Morelli, 2009). It is an approximately 1.9 to 1.84 Ga region of ductile deformation in the Trans-Hudson Orogen, and consists of a complex mixture of Paleoproterozoic volcano-plutonic rocks, representing arc, back arc, ocean plateau and mid ocean ridge environments, and fluvial molasse-type sedimentary rocks (Ansdell and Kyser, 1992; SGS, 2003).

2.3 GEOLOGICAL HISTORY

The chronology of tectonic events that occurred during the Trans-Hudson Orogeny provides a framework for understanding the geological history of the Creighton area. The important phases of the Trans-Hudson Orogeny that produced the present geological conditions observed in the rocks of the region are summarized in Table 1 below. The summary is based primarily on the picture of geodynamic evolution detailed in Fedorowich et al. (1995) but also includes information based on additional detailed work done in the area (Cumming and Scott, 1976; Stauffer and Lewry, 1993; Fedorowich et al., 1993; Ansdell et al., 2005; Corrigan et al., 2005; Hajnal et al., 2005; Corrigan et al., 2007; Whitmeyer and Karlstrom, 2007; Corrigan et al., 2009). In general, there is a characteristic pattern to the tectonic history that includes early stage brittle, to ductile, to brittle-ductile and finally to late brittle deformation over a period of almost 200 million years (Fedorowich et al., 1995), followed by a much more protracted history of localized brittle deformation that may have continued into the Mesozoic Era.

Around 2.075 Ga, initial deposition of the Wollaston Supergroup took place in a passive to incipient rift setting on the eastern side of the Hearne craton. To the east of the Hearne craton, a series of arc oceanic assemblages, including the ca. 1.906 to 1.886 Ga Amisk Group volcanic rocks (Flin Flon greenstone belt) (Gordon et al., 1990; Heaman et al., 1992) coexisted in the Manikewan ocean. During the period between approximately 1.886 and 1.865 Ga, the Manikewan ocean was closing and bringing together the various arc assemblages against each other and the Hearne craton, resulting in the formation of the Wollaston, Rottenstone and La Ronge domains, and the Flin Flon-Glennie complex.

A reversal of subduction polarity between approximately 1.865 and 1.85 Ga is associated with emplacement of the Wathaman batholith, as well as the oldest post-accretionary plutons recognized in the Flin Flon greenstone belt, such as the Annabel Lake pluton (ca. 1.86 Ga), the Kaminis (ca. 1.856 Ga) and Reynard Lake plutons (ca. 1.853 Ga) (Ansdell and Kyser, 1990). These plutons are shown on Figure 3. Ongoing subduction between approximately 1.85 and 1.845 Ga resulted in the accretion of the Flin Flon-Glennie complex (including the Flin Flon greenstone belt) to the Hearne craton. Post-orogenic unconformable deposition of the sedimentary rocks of the Missi Group between ca. 1.847 and 1.842 Ga (Ansdell, 1993) upon the Flin Flon greenstone belt occurred during approximately the same timeframe. Northward migration of the Sask craton micro-continent close to the Flin Flon-Glennie complex may have also occurred during this period.

Table 1 Summary of the geological and structural history of the Creighton area.

Time period (Ga)	Geological event
ca. 2.075	Passive margin phase associated with initiation of deposition of the Wollaston Supergroup on the eastern margin of the Hearne craton. Manikewan ocean opens at the east of Hearne craton.
1.906 to 1.886	A series of volcanic assemblages, including the La Ronge-Lynn Lake arc and a series of arc oceanic assemblages (including Amisk Group/Flin Flon greenstone belt), coexisted in the Manikewan ocean.
1.886 to 1.86	Closure of Manikewan ocean produced accretion of various tectonic assemblages resulting in the formation of the Flin Flon-Glennie complex. Activation of earliest regional shear zones. [D_1]
1.86 to 1.834	Ongoing subduction and accretion during collision induces crustal thickening, thrust faulting and shear zone activation, and on-going folding. [D_2] Deposition of the Missi Group between ca. 1.847 and 1.842 Ga. Emplacement of successor arc intrusions between ca. 1.86 and 1.834 Ga (including the Annabel and Reynard Lake plutons).
1.83 to 1.79	Terminal collision of Trans-Hudson Orogen and final closure of the Manikewan ocean under conditions of peak metamorphism. Transpressional reactivation of regional shear zones, including Needle Falls shear zone and Tabbernor fault zone. [D_3]. Ductile shear zones form along the margins of the granitic intrusions.
1.79 to 1.76	Reactivation of regional shear zones as strike-slip fault zones and onset of retrograde metamorphic conditions. Development of NE-trending regional folds (i.e., the Embury Lake Flexure) and reactivation of regional shear zones. [D_4]
1.725 to 1.691	Brittle faulting and brittle reactivation of regional-scale faults and shear zones. [D_5]
post-1.691	Reactivation of regional scale brittle faults, e.g., Tabbernor fault system. [D_6]

Between approximately 1.845 and 1.83 Ga, the Rae-Hearne craton was thrust upon the Sask craton along the Pelican thrust. This event also overprinted the Annabel Lake and Reynard Lake plutons, the Flin Flon greenstone belt and the rocks of the Missi Group (Figure 3). The Boot Lake and Phantom Lake plutons were emplaced at approximately 1.838 Ga (Heaman et al., 1992), or possibly as late as approximately 1.834 Ga (Ansdell and Kyser, 1990). Magmatism seems to have ended rather abruptly after this time, as no younger plutons have been recognized in the area.

Terminal collision with the Superior craton and final closure of the Manikewan ocean occurred between approximately 1.83 and 1.79 Ga (Fedorowich et al., 1995; Corrigan et al., 2005, 2009).

Crustal shortening that occurred during this period resulted in the initiation of the Needle Falls shear zone (ca. 1.83 Ga), the Tabbernor fault zone (ca. 1.815 Ga) and the steeply-dipping brittle faults observed within the Wollaston Domain (Hajnal et al., 1996; Davies, 1998). Ductile shear zones mapped along the margins of the plutons in the Creighton area were also formed at this time. The shear zones record evidence of activation during peak metamorphic conditions that took place between approximately 1.82 and 1.79 Ga. The resultant greenschist to amphibolite facies metamorphic overprint is recognized throughout the Creighton area.

Later during (or after) the terminal collision, a regional northerly structural trend is folded into an east-trending orientation (e.g., the Embury Lake Flexure) and both local (e.g., Annabel Lake, West Arm and Mosher Lake) and regional scale (e.g., Needle Falls) shear zones were re-activated as strike-slip structures. Subsequent regional-scale brittle faulting, including brittle re-activation of regional scale faults and shear zones, occurred between approximately 1.725 and 1.695 Ga. Cooling ages of vein minerals within the reactivated shear zones constrain the minimum age for fault re-activation at ca. 1.691 Ga. Although poorly constrained in terms of actual timing, there is also evidence of localized, post-1.691 Ga, brittle faulting. This includes late movement along structures associated with the Tabbernor fault system that suggest a long history of re-activation that may have continued until the Mesozoic Era (e.g., Byers, 1962; Elliott, 1996).

Phanerozoic rocks (i.e., rocks younger than 541 million years old) of the Western Canada Sedimentary Basin unconformably overlie Precambrian basement rocks over the entire southern half of Saskatchewan. The present day zero thickness erosional edge of the basin trends northwesterly across the province to the south of the Creighton area. Regional Phanerozoic depocentres of the Hudson Bay and the Western Canada Sedimentary basins, preserved to the northeast and south of the exposed Precambrian basement rocks in northern Saskatchewan, respectively, suggest that the sedimentary cover was formerly much more extensive. Much of the present surface of the Canadian Shield lies close to an exhumed paleoplain interpreted to be of Ordovician age (Brown et al., 1995).

Paleozoic sedimentary rocks of Ordovician age (i.e., 485 to 443 million years old) unconformably overlie the Precambrian basement approximately 20 km south of the Creighton area. These rocks represent a remnant of the Cambrian to Devonian sedimentary succession that was deposited while much of the Churchill Province was inundated by shallow seas during the Paleozoic Era. Given the close proximity of the Western Canada Sedimentary Basin to the south and the apparent continuation of the sequence in the Hudson Bay area of Manitoba to the northeast suggests that the Creighton area was also previously covered by an undetermined amount of Paleozoic strata.

A long period of uplift, exposure and erosion separated the Paleozoic strata from the overlying Mesozoic strata. The erosional edge of the Mesozoic succession, located just over 100 km to the west of Creighton, is characterized by sedimentary rocks of Cretaceous age (145 to 66 Ma old). A few isolated outliers of Cretaceous sedimentary rocks are preserved in closer proximity to Creighton along the southern extension of the Tabbernor Fault. The Mesozoic strata were deposited during a series of regressions and transgressions of the Cretaceous sea over the western interior of North America (Mossop and Shetsen, 1994). The prior extent of Mesozoic cover in the Creighton area, if any, is uncertain.

2.4 Structural History

Fedorowich et al. (1995) describe a structural history that is consistent with the regional geological events described above. This synthesis is based on the results from detailed structural and thermochronological analyses, primarily focused on the study of shear zones in the Flin Flon area. The structural history includes five main episodes of deformation (D_1 – D_5), and provides a relative temporal framework for the sequence of geological events described above. A later D_6 event is included herein to represent the protracted continuation of late brittle deformation until as recently as the Mesozoic Era.

D_1 deformation, attributed to north-south collision, is recognized by the development of vein arrays, thrust faulting and an early phase of folding within the ca. 1.906 to 1.886 Ga Amisk Group, but well prior to deposition of the 1.847 to 1.842 Ga Missi Group. Kinematic and geochronological evidence constrain D_1 to have occurred between ca. 1.886 and 1.860 Ga. D_2 is characterized by continued movement along thrust faults and associated fold development and is considered to have been synchronous with the peak episode of crustal thickening. D_2 is constrained to have occurred between ca. 1.860 and 1.840 Ga and therefore was on-going during deposition of the Missi Group. The crustal thickening resulted in a period of syntectonic granitic activity that also continued until ca. 1.840 Ga. D_3 produced folds and associated axial planar foliations, as well as a number of oblique-slip sinistral reverse shear zones and coincided with peak metamorphic conditions. Regional relationships indicate that the D_3 event was associated with a post-thickening period of ESE-WNW oriented transpression between ca. 1.820 and 1.790 Ga. D_4 represents the timing of activation of strike-slip shear zones, and the re-activation of some pre-existing faults under retrograde metamorphic conditions. D_4 also produced the Embury Lake flexure, the dominant map-scale fold structure in the Creighton area. D_4 is constrained to have occurred between ca. 1.790 and 1.760 Ga. D_5 is characterized by late stage brittle oblique- and strike-slip movement under conditions of NW-SE compression at ca. 1.691 Ga. Protracted, post-1.691 Ga brittle re-activation of faults throughout the Creighton area is collectively attributed to a D_6 deformation event.

2.5 LOCAL BEDROCK GEOLOGY

The reader is directed to Golder (2013) for a detailed description and discussion of the bedrock and structural geology of the Creighton area. The regional bedrock geology of the Creighton area is dominated by the Flin Flon greenstone belt that is intruded by several large felsic plutonic bodies (Figure 3). The geological boundaries shown on this figure are from the Geological Atlas of Saskatchewan and the NATMAP Shield Margin project (NATMAP, 1998; Saskatchewan Energy and Resources, 2010).

The Flin Flon greenstone belt has been the target of many drilling programs associated with mineral exploration and mining activities in the area. Rocks of the Flin Flon greenstone belt include mostly juvenile ocean arc and ocean floor assemblages. Recently these rocks have been collectively called the Flin Flon Arc assemblage (Lucas et al., 1999; Simard et al., 2010). However due to historical usage, the original terminology of Flin Flon greenstone belt, or simply greenstone belt, will be retained throughout the remainder of the report when discussing the bedrock geology of the Creighton area.

The Flin Flon greenstone belt includes mafic volcanic flows, pyroclastic rocks, lesser amounts of intermediate to felsic volcanic rocks, and metasedimentary rocks that are arranged in layers of variable thickness and have been deformed by past tectonic events (Simard et al., 2010). The rocks of the Flin Flon greenstone belt are intruded by felsic to intermediate intrusive rocks of the Annabel Lake pluton, Reynard Lake pluton and Phantom-Boot Lake pluton (Figure 3). It is these three plutons that offer the most promise for a suitable siting selection, as identified in the Initial Screening study by Golder Associates (2011). Areas mapped as either rock outcrop or rock thinly covered (< 0.5 m) by surficial materials or as a discontinuous till veneer (< 1.0 m) interspersed with rock outcrop account for about 38% of the portion of the Creighton area not covered by water. In comparison, the Annabel Lake and Reynard Lake plutons exhibit higher percentages of this terrain characteristic (47% and 51%, respectively) and the Phantom-Boot Lake pluton exhibits a lower percentage (23%).

2.5.1 Reynard Lake Pluton

The Reynard Lake pluton is located approximately 5 km southwest of Creighton, and extends approximately 25 km to the northwest. As can be seen on Figure 3, the pluton is tear-drop shaped, with its lobe situated at the southeast end of the pluton. The lobe is approximately 6 km wide at the pluton's widest point. The Reynard Lake pluton is inferred to have intruded the older Flin Flon greenstone belt during the Trans-Hudson Orogeny. The pluton is estimated to be approximately 1.853 Ga old, based on dating using the single-zircon Pb-evaporation technique (Ansdell and Kyser, 1992).

Surface mapping of the Reynard Lake pluton indicates that it consists of a central core of coarse-grained porphyritic microcline granite. The large microcline phenocrysts have a pink to buff colour and are surrounded by a medium- to coarse-grained light pink to grey groundmass. The central core of the pluton is surrounded by a shell of discontinuous nonprophyritic biotite granodirorite. This biotite granodiorite is medium-grained with a white to pinkish colour. The margins of the pluton are generally marked by sharp contacts with metavolcanic rocks (Bunker and Bush, 1982). Two distinct foliations have been observed in the area, the first of which has a northerly trend, followed by a younger set conforming to the boundaries of the intrusive bodies. Core samples were obtained from a deep borehole (JXWS) drilled into the Reynard lake pluton at approximately 300 m intervals (Bunker and Bush, 1982; Davis and Tammemagi, 1982). The generalized lithology encountered within this drill hole consisted of pink to grey, medium-grained granodiorite to mafic granodiorite to approximately 450 m depth, followed by grey to light grey quartz diorite to approximately 2,250 m depth, in turn underlain by very dark, fine-grained mafic quartz diorite to the termination of the drill hole. The contacts between these three lithologic zones are broadly transitional (Davis and Tammemagi, 1982).

2.5.2 Annabel Lake Pluton

The Annabel Lake pluton is located approximately 3 km to the northwest of the settlement of Creighton, extending 25 km further to the west. This pluton is elongated parallel to regional east- to southeast-trending shear zones along its boundaries (Figure 3). The pluton is widest (approximately 5 km) at its southeast end.

The Annabel Lake pluton was formed approximately 1.86 Ga, based on dating by Ansdell and Kyser (1990). The pluton consists of medium to coarse grained, foliated granodiorite, containing quartz, feldspar, biotite and hornblende. No specific information is available regarding the compositional homogeneity of the pluton. However, given its similar geological history to the

Reynard Lake pluton, the Annabel Lake pluton is expected to have generally similar compositional zoning.

No specific information at depth within the Annabel Lake pluton was found through available sources. However, based on geophysical modeling, the maximum depth of the pluton is likely in the range of 5 to 5.5 km (White et al., 2005). A conceptual cross-section of the Annabel Lake pluton is provided by Simard et al. (2010) along with detailed 1:10,000 scale mapping of the area.

2.5.3 Phantom-Boot Lake Pluton

The Phantom-Boot Lake pluton is located approximately 2 km to the south of the settlement of Creighton. Compared to Reynard Lake and Annabel Lake plutons, the Phantom-Boot Lake pluton is a relatively small intrusive body, measuring approximately 6 km in length (north to south) and 2 km in width (east to west) (Figure 3). Surface exposure of this pluton is relatively limited (Guliov, 1989).

The Phantom-Boot Lake pluton is considered a successor-arc intrusion that was emplaced later in the tectonic evolution of the area (i.e., post-Missi Group intrusion) and at shallower depths than the Reynard Lake and Annabel Lake plutons (Ansdell and Kyser, 1990; NATMAP, 1998; and Simard et al., 2010). The pluton consists of two intrusions that are considered coeval. Ansdell and Kyser (1990) dated a granodiorite phase of the Boot Lake pluton at approximately 1.842 Ga old and a granite phase of the Phantom Lake pluton at approximately 1.840 Ga old, respectively. They also obtained an age of approximately 1.834 Ga for the associated granite dykes of the Phantom Lake pluton. Heaman et al. (1992) also obtained an age of approximately 1.838 Ga for both a monzogranodiorite phase of the Boot Lake pluton and a granodiorite phase of the Phantom Lake pluton.

The Phantom Lake pluton is a fine- to medium-grained porphyritic pink granodiorite-tonalite with a massive to banded texture (Guliov, 1989; Simard et al., 2010). This portion of the pluton occurs along the southwest shore of Phantom Lake. The Boot Lake pluton wraps around the Phantom Lake pluton to the west, southwest, and through to the south. The Boot Lake pluton is zoned and has been further subdivided into two general rock types including a granodiorite to quartz diorite, and quartz-diorite to gabbro (Simard et al., 2010).

2.5.4 Flin Flon Greenstone Belt

The majority of the Town of Creighton itself is underlain by metavolcanic rocks of the Flin Flon greenstone belt. These rocks extend to the north, east, southeast and southwest of the Town. Four tectono-stratigraphic assemblages have been recognized within the Flin Flon greenstone belt. These include: juvenile oceanic arc (ca. 1.9 to 1.88 Ga), oceanic floor (ca. 1.9 Ga), oceanic plateau/ocean island (undated), and evolved arc (ca. 1.92 to 1.9 Ga), which were formerly known collectively as the Amisk Group (ca. 1.92 to 1.88 Ga), (Bailes and Syme, 1989; Syme et al., 1996; and Bailey and Gibson, 2004).

Rocks of the Flin Flon greenstone belt within the Creighton area include mostly juvenile ocean arc and ocean floor assemblages. These rocks are the oldest in the Creighton area, and they consist of basic volcanic flows, pyroclastic rocks, and lesser amounts of acidic to intermediate volcanic rocks and clastic rocks. This assemblage also includes dykes, sills, and small intrusive porphyritic bodies.

Due to the complex structure (folding and faulting) within the Flin Flon greenstone belt, thickness of individual lithologies within the assemblage can be difficult to determine; however, it has been estimated that these rocks are approximately 4 to 6 km thick in the Creighton-Amisk Lake area (Byers and Dahlstrom, 1954; Byers et al., 1965). More recent estimates suggest they are in the order of 10 to 20 km thick (Lucas et al., 1994; Hajnal et al., 1996; White et al., 2005). Rocks of the Flin Flon greenstone belt are heterogeneous and variable in type, and are arranged in layers of variable thickness and lithological compositions (Byers and Dahlstrom, 1954). Past tectonic events deformed these units, making their stratigraphic interpretation difficult (NATMAP, 1998; Simard et al., 2010).

The Flin Flon greenstone belt is unconformably overlain by interlayed metasedimentary conglomerates, greywackes and arkoses of the Missi Group, which is a sequence of synorogenic fluvial molasse deposits (Byers et al., 1965; Davis and Tammemagi, 1982; Ansdell and Kyser, 1990; and Simard et al., 2010).

2.5.5 Metasedimentary rocks of the Missi Group

Missi Group rocks are found to the north and west of the Town. These rocks are interpreted to have been deposited due to regional uplift in a collisional tectonic environment (Fedorowich et al., 1993), and are approximately 1.847 to 1.842 Ga old (Fedorowich et al., 1993). The thickness of the Missi Group rocks is estimated to be approximately 1 to 2.75 km (Byers and Dahlstrom, 1954; Byers et al., 1965).

2.5.6 FAULTS AND SHEAR ZONES

Structural features in the Creighton area include major ductile shear zones, such as the Annabel Lake, West Arm, and Mosher Lake shear zones and numerous brittle faults (Figure 3). This section summarizes the available information on the mapped structures observed in the region.

The Annabel Lake shear zone strikes east along Annabel Lake and Annabel Creek on the northern margin of the Annabel Lake pluton, and is marked by a zone of intense shearing and mylonitization (Byers et al., 1965; Parslow and Gaskarth, 1981). Within the Creighton area, the Annabel Lake shear zone dips sub-vertically to the north. The amount of movement within the Annabel Lake shear zone is unknown but evidence of sinistral movement has been noted by Ashton et al. (2005).

The West Arm shear zone occurs between the Annabel Lake and Reynard Lake plutons, and strikes southeast through Wilson and Meridian Lakes. It is also marked by a zone of intense shearing and mylonitization, and dips sub-vertically to the southwest. The amount of movement in the West Arm shear zone is unknown, but it was sufficient to remove a portion of the south limb of a syncline which occurs in the vicinity of Wilson Lake (Byers et al., 1965).

The Mosher Lake shear zone strikes southeast along the southern margin of the Reynard Lake pluton and joins the West Arm shear zone at its western extent. The Mosher Lake shear zone comprises numerous branching minor faults and zones of alteration (Byers and Dahlstrom, 1954). Although the Mosher Lake shear zone has a component of sinistral displacement, the amount of displacement is unknown (Slimmon, 1995).

Brittle deformation features are mapped to the east and north of the Annabel Lake pluton (Saskatchewan Energy and Resources, 2010). Numerous unnamed faults are located within the greenstone rocks to the east of the pluton. Most of these features are tightly spaced (on the order of 100's of metres) and are parallel to the southern lobe of the pluton. An orthogonal set of faults with a lower frequency and larger spacing (in the order of 2 to 3 km) appears to extend some distance into the pluton. These features are noted to the south and east of Creighton Lake. A set of faults extending through the Annabel Lake shear zone are located near the northeast side of the pluton. These faults generally strike northwest to southeast, and also may extend a short distance into the pluton (Saskatchewan Energy and Resources, 2010). Along the northeast corner of the pluton, the Triangle Lake fault cuts through a portion of the pluton and is parallel to the outer edge of the pluton in this area (Byers et al., 1965).

Brittle deformation is noted along the east edge of the Reynard pluton and within the southernmost portion of the pluton (i.e., to the southeast of Patmore and Reynard Lakes). One set of faults is sub-parallel to the West Arm and Mosher Lake shear zones. These faults have spacing ranging from approximately 500 m to 2.5 km. A roughly orthogonal set may be related to the Mystic Lake fault which strikes northeast-southwest, to the south of the pluton. The spacing of these faults ranges from approximately 200 m to 2 km (Simard et al., 2010).

Brittle deformation features have been mapped around the perimeter of the Phantom-Boot Lake pluton, with the exception of the south, which is predominantly covered by wetlands (noting that much of the pluton itself is covered by wetlands). The Rio fault is located along the northwest edge of the pluton (Simard and MacLachlan, 2009; Simard et al., 2010). This fault separates the northern lobe of quartz-diorite and gabbro from the surrounding greenstones and has been the target of mineral exploration activities near Bootleg Lake (boreholes drilled between 1975 to 1984 available from the SGS Atlas of Saskatchewan; Hudbay Minerals; and Simard et al., 2010).

The Ross Lake fault system consists of several sets of inter-related faults that occur between Schist Lake to the south of the Creighton area (located within Manitoba), and Precipice Lake, approximately 13 km to the north of the Creighton area (Byers, 1962; Fedorowich et al., 1993). The Ross Lake fault system is represented by near vertical north-northeast and north-northwest trending splays of lineaments with a total strike length of over 100 km (Byers, 1962; Fedorowich et al., 1993). The Ross Lake fault system is interpreted to have formed during the fifth deformational stage as it is observed to cross-cut the Embury Lake flexure and the Annabel Lake shear zone (Ansdell and Kyser, 1990; Fedorowich et al., 1993; NATMAP, 1998; Saskatchewan Energy and Resources, 2010). In the northeast portion of the Creighton area, approximately 1,250 m of sinistral oblique reverse displacement has occurred along the Ross Lake fault system (Byers et al., 1965). Although not well identified (due to lack of information), it can be assumed that some of the north-northwesterly trending faults shown within the Flin Flon greenstone belt in the Creighton area may be related to the Ross Lake fault system, as subsidiary movement along several branching faults is associated with this fault system (Byers, 1962).

It is possible that the north-south trending faults in the Creighton area, including the Ross Lake fault, are related to the Tabbernor fault system (Byers, 1962). The Tabbernor fault is located approximately 80 km west of Creighton. This feature initially formed approximately 1.815 Ga during the Trans-Hudson Orogen (Davies, 1998), and likely experienced more recent periods of reactivation (Elliot, 1996). The fault is a topographical, geophysical and geological lineament that extends a distance greater than 1,500 km. In Saskatchewan, the fault zone has a northerly strike and has undergone sinistral movement. Several researchers have suggested that the Tabbernor fault zone was active as recently as the Phanerozoic (Elliot, 1996; Davies, 1998; Kreis et al., 2004), including potential Mesozoic movement (Byers, 1962). As such, evidence of neotectonics may be preserved in younger units overlying the fault zone.

Several smaller parallel faults located within the Phantom-Boot Lake pluton have also been the target of mineral exploration activities. These faults are cut by the Douglas Lake fault, which extends into the northwest lobe of the pluton with a north-south strike. Approximately 200 m (in plan view) of sinistral movement has occurred along the Douglas Lake fault (Simard et al., 2010). At least two other north-south striking faults cut through the northern portion of the pluton with a maximum spacing of approximately 1 km. The Dion Lake fault strikes in a northeast-southwest direction and largely separates the Phantom Lake intrusion to the east from a portion of the Boot Lake intrusions to the west. Due to less detailed mapping in the southern portion of the pluton, less structural information is available. Byers et al. (1965) mapped one fault in the south-central portion of the pluton (southeast of Boot Lake), with a west northwest-east southeast strike. It is possible that this feature cuts through the south end of Boot Lake and may be related to the Mystic Lake fault to the southwest.

2.5.7 METAMORPHISM

Two periods of metamorphic mineral growth appear to have occurred in the Creighton region (Fedorowich et al., 1993). These periods correspond to the D_2 and D_3 deformation events described in Section 2.3 and 2.4 and the two most distinct foliations in the region are defined by phyllosilicates that grew during these periods. The earliest period of metamorphism appears to be related to the intrusion of the major felsic plutons in the area (including the Reynard Lake and Annabel Lake plutons), and consists of alteration due to the slow cooling of magmatic rocks after consolidation resulting in contact aureoles around the plutons (Byers et al., 1965; Fedorowich et al., 1993). This first period of peak low-grade metamorphism initiated in D_2 and was likely maintained up to D_3 (Bailes and Syme, 1989). Locally, an amphibolite grade halo has been noted around the Reynard Lake pluton, suggesting the intrusions locally increased temperatures during their emplacement (Ansdell and Kyser, 1990). The contact aureoles are up to 1 km wide, with hornblende being the dominant amphibole (Galley et al., 1991).

The second stage of metamorphism is related to the D_3 collisional stage of the Trans-Hudson Orogen, where metamorphic conditions peaked approximately 1.826 to 1.805 Ga (Corrigan et al., 2007). This resulted in peak metamorphism to greenschist facies within the Creighton area (Ferguson et al., 1999; Parslow and Gaskarth, 1981), allowing for good preservation of primary textures and structures (Simard and MacLachlan, 2009). This regional metamorphism is superimposed over the earlier contact aureoles surrounding the plutons. Lower greenschist mineral assemblages are characterized by chlorite, tremolite-actinolite, albite, epidote, sericite and quartz (Galley et al., 1991). The contact aureoles around the plutons are locally over-printed by chlorite-actinolite as a result of this stage of regional metamorphism. During this period, a certain amount of hydrothermal alteration occurred around faults and shear zones in the Creighton area (Byers et al., 1965).

Regionally, metamorphic grade generally decreases from the north to the south. To the north of the Creighton area (approximately 10 km, towards the Kisseynew metasedimentary gneiss belt), the grade of metamorphism increases to upper amphibolite facies (Galley et al., 1991; Fedorowich et al., 1993). In this higher grade area to the north, retrograde lower greenschist mineral assemblages are reported in D_5 faults (Byers et al., 1965). Further south, metamorphic grade decreases from middle greenschist (biotite) in the Ross Lake (Flin Flon) area, to subgreenschist (prehnite-pumpellite) in the White Lake area approximately 8 km southeast of Creighton (Bailes and Syme, 1989; Galley et al., 1991).

2.6 QUATERNARY GEOLOGY

Quaternary geology of the Creighton area is described in detail in a separate terrain analysis report by JDMA (2013). Quaternary deposits (including till veneer) not covered by water account for a total of 377 km^2 or roughly 57% of the Creighton area (Figure 4). Drift cover in much of the Creighton area is generally thin (less than 2 m) and discontinuous (Henderson, 1995), although sonic and wacker drilling indicates that drift thickness is highly variable, with depths exceeding 90 m indicated in topographic lows (Saskatchewan Industry and Resources, 2010). High relief bedrock topography in parts of the Creighton area is responsible for wide variations in drift thickness over short lateral distances (Campbell, 1988). Information on drift thickness from SGS drill holes is consistent with the statements above (JDMA, 2013).

Glacial sediments in the Creighton area record advances of the Keewatin ice sheet during and after the last glacial maximum, known as the Late Wisconsinan glaciation (McMartin et al., 2012). The most extensively distributed till formation is a generally sandy till overlying bedrock

(Henderson and Campbell, 1992), whereas a younger formation occurring as thin and discontinuous deposits of flow till overlying glaciolacustrine sediments, and in places incorporating clasts of glaciolacustrine material, record a readvance into glacial Lake Agassiz (Campbell, 1988). The younger till occurs east of Amisk Lake and north of Annabel Lake.

The main ice flow direction in the area was to the south-southwest, indicating glaciation from a dispersal centre in the District of Keewatin, but there are distinct differences in the record of ice flow indicators north and south of Annabel Lake (Henderson, 1995). South of Annabel Lake the dominant ice flow direction is south-southwest, as indicated by striated bedrock outcrops and by the orientation of roches moutonneés along the east and west shores of Amisk Lake. This dominant ice flow direction is recorded in a few places north of Annabel Lake, but in general, it has been obliterated in this area by a readvance to the southwest. A subaqueous outwash deposit 3 to 5 km wide has been mapped north of Annabel Lake, along which a large part of Highway 106 in this area has been routed. Henderson (1995) interprets this feature as an end moraine based on its positive topographic expression and that it marks the southern limit of the southwest striae.

The entire area was flooded by glacial Lake Agassiz (Campbell, 1988; Henderson, 1995), with maximum lake level estimated by Schreiner (1984) to be between 400 and 427 m. Nearshore and offshore glaciolacustrine sediments have been mapped. Nearshore sediments consist of well-sorted, generally horizontally stratified sand and gravel normally found below the 350 m elevation (Henderson and Campbell, 1992). Offshore sediments consist of massive to rhythmically bedded fine sand, silt and clay typically deposited below 340 m elevation. Offshore sediments are found extensively along the margins of Amisk Lake (Figure 4). Glaciolacustrine deposits commonly form a blanket over previously deposited sediments, with thicker deposits in depressions.

2.7 LAND USE

Land use within the Creighton area includes the population centres of Creighton and Flin Flon where there are extensive mining operations. There are also road corridors along highways 106 and 167 that provide good site accessibility (JDMA, 2013). These land use and cultural features do not negatively impact on the interpretation of bedrock lineaments.

3 METHODOLOGY

3.1 SOURCE DATA DESCRIPTIONS

The lineament interpretation was conducted using available surficial (CDED and SRTM digital elevation models, SPOT satellite imagery), and geophysical (aeromagnetic) datasets for the Creighton area. Available data were assessed for quality, processed and reviewed before use in the lineament interpretation. SPOT and DEM datasets were used to identify surficial lineaments expressed in the topography, drainage, and vegetation. The resolution of the SPOT and DEM datasets allowed for the identification of surficial lineaments as short as a few hundred metres in length and provided sufficient detail to reveal surficial structural patterns. The geophysical data, in particular aeromagnetic data, were used to evaluate deeper bedrock structures. Comparing SPOT and DEM lineaments to aeromagnetic lineaments allows for the comparison of subsurface and surficial expressions of the bedrock structure. Both the SPOT and DEM datasets offered advantages to characterize the surficial lineaments. The higher resolution of the SPOT imagery allowed for finer structures to be identified that were not resolved by the DEM data; but, the DEM data often revealed subtle trends masked by the surficial cover captured in the SPOT imagery. The aeromagnetic data proved invaluable to identify bedrock structures beneath areas of extensive surficial cover and to aid in establishing the age relationships among the different lineament sets. Table 2 provides a summary of the source datasets used for the lineament interpretation.

3.1.1 SURFICIAL DATA

DEM (Digital Elevation Model)

Canadian Digital Elevation Data (CDED) and Shuttle Radar Topography Mission (SRTM) elevation models served as important data sources for analyzing and interpreting the terrain in the Creighton area. The CDED, 1:50,000 scale, 0.75 arc second (20 m) elevation model (GeoBase, 2011a) used for this study, shown as a slope raster in Figure 5, was constructed by the Mapping Information Branch of Natural Resources Canada (NRCan) and by the Landscape Analysis and Applications section of the Canadian Forest Service using 1:50,000 scale source data from the National Topographic Data Base (NTDB). The source data were produced by the Surveys and Mapping Branch of Energy, Mines and Resources Canada based on black and white air photographs acquired mainly in the 1950s at scales of 1:60,000 to 1:70,000. Four main NTDB data types were used: contours, spot heights, streams, and lakes. CDED datasets are provided in geographic coordinates, referenced horizontally using North American Datum 1983 (NAD83) and vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28). Ground elevations are recorded in metres relative to mean sea level.

Table 2 Summary of source data information for the lineament interpretation of the Creighton area.

Dataset	Product	Source	Resolution	Coverage	Acquired	Additional Comments
DEM	Canadian Digital Elevation Data (CDED); 1:50,000 scale	Geobase	20 m	Entire area	1978 - 1995	Hillshaded and slope rasters used for mapping
	Shuttle Radar Topography Mission (SRTM)	CGIAR	90 m	Entire area	2000	Hillshaded and slope rasters used for mapping
Satellite Imagery	SPOT 4/5; Orthoimage, multispectral/ panchromatic	Geobase	10 m (panchromatic) 20 m (multispectral)	Entire area	2005 - 2006	Panchromatic mosaic used for mapping
Geophysics	Flin A	Hudbay	200 m line spacing Sensor height 40 m (VTEM) 60 m (mag)	Covers 288.2 km^2 in east-central part of area	2007	Priority 1 in overlapping areas
	Konuto	Hudbay	200 m line spacing Sensor height 40 m (VTEM) 63 m (mag)	Covers 86.0 km^2 in south - central part of area	2008	Priority 2 in overlapping areas
	Flin Flon-Sherridon A (magnetic and VLF-EM)	GSC	300 m line spacing Sensor height 150 m	Covers 1,325.8 km^2 mainly in north and west parts of area	1986	Priority 5 in overlapping areas
	Flin Flon-Sherridon B (magnetic and VLF-EM)	GSC	300 m line spacing Sensor height 150 m	Covers 306.2 km^2 in south part of area	1986	Priority 4 in overlapping areas
	Flin Flon (Queenair) (magnetic and VLF-EM)	GSC	300 m line spacing Sensor height 150 m	Covers 235.5 km^2 in east part of area	1980	Priority 3 in overlapping areas
	Hanson Lake (magnetic, radiometric and VLF-EM)	GSC	500 m line spacing Sensor height 120 m	Covers 1,885.4 km^2 in all but south part of area	1993	Other surveys superior for magnetics

GSC – Geological Survey of Canada
VTEM – Versatile Time Domain Electromagnetic
VLF-EM – Very Low Frequency Electromagnetic
THOT – Trans-Hudson Orogen Transect
CGIAR – Consultative Group on International Agricultural Research

CDED lacked sufficient detail on the eastern portion of the study area. Therefore, SRTM digital elevation data were used to supplement CDED in this area. The SRTM data were produced by a specially designed radar system that flew onboard the Space Shuttle Endeavor. The imagery was taken in February, 2000. The SRTM data were released in 2003 after being processed by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). For all landmasses outside of the United States, including Canada, the product was downsampled from 1-arcsecond to 3-arcseconds. SRTM data are available from the Consultative Group on International Agricultural Research – Consortium for Spatial Information (CGIAR-CSI). It was determined that the resolution of the CDED and SRTM data was sufficient to undertake the lineament interpretation.

CDED and SRTM files were transferred from geographic coordinates to UTM projection using bilinear resampling, which assigns a value to each output cell based on a weighted average of the four nearest cells in the input raster. Compared with cubic convolution, bilinear resampling can sometimes produce a noticeably smoother surface, whereas cubic convolution can produce a sharper image. However, the differences between the two methods are generally trivial and the selection of bilinear resampling was arbitrary. The projected files were then assembled into a mosaic (Figure 5). Table 3 lists the CDED tiles used in the final mosaic.

Hillshaded elevation data was built using the CDED and SRTM elevation data. The hillshades were built using illuminated azimuths of 045 and 315º and solar incidence angles of 45º from horizon. Slope was calculated using the standard grid-based method employed in ArcGIS, which involves fitting a plane to the elevation values of a three by three neighbourhood centred on the processing cell. Slope is defined as the maximum slope of that plane, which can also be thought of as the dip of the plane, and aspect is equivalent to the dip direction. Figure 5 shows the calculated slope from the CDED elevation data for the Creighton area. The hillshade and slope rasters were most useful for mapping lineaments.

Table 3 Summary of 1:50,000 scale CDED tiles used for lineament interpretation.

NTS Tiles:	Ground Resolution (arcsec.)
63L/ 09	0.75
63L/ 16	0.75
63K/ 12-13	0.75

SPOT (Système Pour l'Observation de la Terre) Imagery

SPOT multispectral (20 m resolution) and panchromatic (10 m resolution) orthoimagery (the latter is shown on Figure 6) were used for identifying surficial lineaments and exposed bedrock within the Creighton area (GeoBase, 2011b). SPOT multispectral data consist of several bands, each recording reflected radiation within a particular spectral range, and each having a radiometry of 8-bits (or a value ranging from 0 to 255). SPOT 4 and 5 images were acquired using the HRV-IR and HRG sensors, respectively. Each image covers a ground area of 60 km by 60 km. Four SPOT images (scenes) provided complete coverage for the Creighton area (Table 4). The scenes are from both SPOT 4 and 5 satellites acquired between 2005 and 2006, with all scenes acquired in September.

Table 4 Summary of SPOT imagery used for lineament interpretation.

Scene ID	Satellite	Date of image
S4_10146_5435_20050920	SPOT 4	September 20, 2005
S5_10243_5435_20060902	SPOT 5	September 2, 2006
S5_10229_5503_20060902	SPOT 5	September 2, 2006
S4_10135_5503_20060919	SPOT 4	September 19, 2006

For quality control, Natural Resources Canada (NRCan) provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15º. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, projected using Universal Transverse Mercator (UTM) projection referenced to the North American Datum 1983 (NAD83). It was determined that the resolution of the SPOT dataset was sufficient to undertake the lineament interpretation. The scenes were processed to create a single panchromatic mosaic (Figure 6; JDMA, 2013). An automated contrast matching technique was applied to the images which minimizes sharp variances in pixel intensity, giving the single image a cohesive appearance. The images were extended beyond the defined boundaries of the Creighton area to allow for the mapping of continuous lineaments extending beyond the Creighton area.

3.1.2 GEOPHYSICAL DATA

The geophysical dataset incorporates aeromagnetic, gravity and radiometric data available across the entire Creighton area, however only aeromagnetic data were used for this lineament interpretation. The coarse resolution of the gravity and radiometric data were insufficient to interpret lineaments. Table 2 provides a summary of the acquisition parameters for each aeromagnetic dataset used. The magnetic data located within the Creighton area were processed using several common geophysical techniques in order to enhance the magnetic response to assist with the interpretation of geophysical lineaments. The enhanced magnetic grids used in the lineament interpretation include the first and second vertical derivatives, and the tilt angle filter grids. These enhanced grids were processed and imaged using the Geosoft Oasis montaj software package. Acquisition parameters, processing methods and enhanced grids associated with the geophysical datasets used in the lineament interpretation are discussed in detail in PGW (2013). Three additional magnetic grids using a combination of gradient and amplitude equalization filters were prepared using the Encom (Pitney Bowes) Profile Analyst software package in order to highlight the edges of magnetic sources. The combination of all of the enhanced magnetic grids provide much improved resolution of subtle magnetic fabrics and boundaries in areas that appear featureless in the total magnetic field. Figure 7 shows a compilation of the total field (reduced to pole) of each of these aeromagnetic datasets.

The quality of geophysical data varied across the Creighton area. The quality of the data is a function of the flight line spacing, the flying height and the age of the survey. The integrity of the higher quality data was maintained throughout. It was determined that overall the quality of the data was sufficient to perform the lineament interpretation at the scale of the Creighton area.

The Creighton area is entirely covered by medium-resolution aeromagnetic data published by the Geological Survey of Canada (GSC) and downloaded from their Geoscience Data Repository for Geophysical and Geochemical Data (GSC, 2012). The data was acquired at 300 m and 500 m flight line spacing.

Two higher resolution magnetic and versatile time domain electromagnetic surveys (Flin A and Konuto) conducted by Hudbay provided coverage of the east-central and south central areas. These higher resolution surveys were flown at a lower terrain clearance compared to the GSC datasets, with tighter flight line spacing providing these surveys with a relatively high spatial resolution. These surveys focused primarily on exploration in the greenstone belts, with moderate coverage of the plutonic rocks.

3.2 LINEAMENT INTERPRETATION WORKFLOW

Lineaments were interpreted using a workflow designed to address issues of subjectivity and reproducibility that are inherent to any lineament interpretation. The workflow follows a set of detailed guidelines using publicly available surficial (DEM, SPOT) and geophysical (aeromagnetic) datasets as described above. The interpretation guidelines for brittle and dyke lineaments involved three steps:

1. Identification of lineaments by two interpreters for each dataset (DEM, SPOT, MAG) and assignment of certainty level (1, 2 or 3);
2. Integration of lineament interpretations by dataset (Figures 8, 9, 10) and first determination of reproducibility (RA_1); and
3. Integration of lineament interpretations for all three datasets (Figures 12 and 13) and determination of coincidence (RA_2).

Ductile geophysical lineaments, including all interpreted features which conform to the penetrative rock fabric in the Creighton area, such as stratigraphic and foliation traces and litho-structural contacts, were picked using the aeromagnetic geophysical survey data by an automated picking routine with confirmation by a single documented specialist observer (Figure 11).

Each identified lineament feature was classified in an attribute table in ArcGIS. The description of the attribute fields used is included in Table 6. Fields 1 to 9 are populated during the first step. Fields 10 and 11 are populated during the second step. Fields 12 to 19 are populated in the third and final step.

A detailed description of the three workflow steps, as well as the way each associated attribute field is populated for each interpreted brittle or dyke lineament is provided below.

3.2.1 STEP 1: LINEAMENT IDENTIFICATION AND CERTAINTY LEVEL

The first step of the lineament interpretation was to have each individual interpreter independently produce GIS lineament maps, and detailed attribute tables, for each of the three datasets. This action resulted in the production of two interpretations for each of the DEM, SPOT, and aeromagnetic datasets and a total of six individual GIS layer-based interpretations. Each interpreter assigned a certainty/uncertainty descriptor (attribute field 'Certain' = 1-low, 2-medium or 3-high) to each feature in their interpretation based on their judgment concerning the clarity of the lineament within the dataset. Where a surface lineament could be clearly seen on exposed bedrock, it was assigned a certainty value of 3. Where a lineament represented a bedrock feature that was inferred from linear features, such as orientation of lakes or streams or linear trends in texture, it was assigned a certainty value of either 1 or 2. For geophysical lineaments, a certainty value of 3 was assigned when a clear magnetic susceptibility contrast could be discerned and a certainty value of either 1 or 2 was assigned when the signal was discontinuous or more diffuse in nature. The certainty classification for all three datasets ultimately came down to expert judgment and experience of the interpreter.

The geophysical dataset also allowed the interpreter to assess the brittle feature type of the lineaments. The brittle geophysical lineaments interpreted as linear fractures exhibit magnetic signals that are lower than the surrounding bedrock. Where clear offsets can be determined, the brittle fractures can be further characterized as faults, and attributed accordingly.

It is understood that some of the lineament attributes (e.g., width and relative age) will be further refined as more detailed information becomes available in subsequent stages of characterization should the community be selected by the NWMO and remain interested in advancing in the site selection process.

Table 5 Summary of attribute table fields populated for the lineament interpretation.

	Attribute	Brief Description
1	Rev_ID	Reviewer initials
2	Feat_ID	Feature identifier
3	Data_typ	Dataset used (DEM, SPOT, Geophys)
4	Feat_typ	Type of feature used to identify each lineament
5	Name	Name of feature (if known)
6	Certain	Certainty value (1-low, 2-medium or 3-high)
7	Length*	Length of feature is the sum of individual lengths of mapped polylines (not end to end) and is expressed in kilometres
8	Width**	Width of feature; This assessment is categorized into 5 bin classes: A. < 100 m B. 100 – 250 m C. 250 – 500 m D. 500 – 1,000 m E. > 1,000 m
9	Azimuth	Vector average direction of all line segments forming the lineament (1 – 180°)
10	Buffer_RA_1	Buffer zone width for first reproducibility assessment
11	RA_1	Feature value (1 or 2) based on first reproducibility assessment
12	Buffer_RA_2	Buffer zone width for second reproducibility assessment
13	RA_2	Feature value (1, 2 or 3) based on second reproducibility assessment (i.e., coincidence)

	Attribute	Brief Description
14	Geophys	Feature identified in geophysical dataset (Yes or No)
15	DEM	Feature identified in DEM dataset (Yes or No)
16	SPOT	Feature identified in SPOT dataset (Yes or No)
17	F_Width	Final interpretation of the width of feature
18	Rel_age	Relative age of feature, in accord with regional structural history
19	Notes	Comment field for additional relevant information on a feature

* The length of each interpreted feature is calculated based on the sum of all segment lengths that make up that lineament.

**The width of each interpreted feature is determined by expert judgment and utilization of a GIS-based measurement tool. Width determination takes into account the nature of the feature as assigned in the Feature type (Feat_typ) attribute.

3.2.2 Step 2: Reproducibility assessment 1 (RA_1)

The two individual GIS lineament maps from each dataset were then integrated to provide a single interpretation for the DEM (Figure 8), SPOT (Figure 9) and aeromagnetic (Figure 10) data that included the results of the first stage reproducibility assessment (RA_1). Reproducibility is judged based on the coincidence, or lack thereof, of interpreted lineaments within an assigned buffer zone. For example, if a lineament was identified by both interpreters within an overlapping buffer zone, then it was deemed coincident and assigned a reproducibility value of two (RA_1 = 2). An initial buffer zone width (Buffer_RA_1) of 200 m was selected to evaluate coincidence. For many of the lineaments, coincidence could be demonstrated with a smaller buffer width, and in these cases a buffer width of either 100 m or 50 m, depending on the maximum offset, was entered in the attribute field. Where a lineament was identified by only one of the interpreters, it received a buffer zone width of zero (Buffer_RA1 = 0) and a reproducibility value of one (RA_1 = 1) in the attribute table.

Where coincident interpreted lineaments were identified, the one line that appeared to best represent the surficial or geophysical expression of the feature (based on the judgment of the integrator) was retained and assigned attributes. In some instances, where deemed appropriate, either an existing line was edited or a new line was drawn as part of the merging process to best capture the expression of the lineament. The decision of whether to retain or edit an existing line, or to draw a new line, was based largely on expert judgment that followed these guidelines: 1) where one continuous lineament was drawn by one interpreter, but as individual, spaced or disconnected segments by the other, a single continuous lineament was carried forward with a reproducibility value of two (RA_1 = 2) provided that the continuous lineament was deemed a better representation of the feature; and 2) where two interpreted lineaments were coincident over less than three-quarters of the total length of the longest lineament, the longest lineament was segmented and each portion was attributed with RA_1 values accordingly. Otherwise, if the two lineaments were coincident for more than three-quarters of the length of the longer lineament, they were considered coincident and assigned a reproducibility value of two (RA_1 = 2).

3.2.3 STEP 3: REPRODUCIBILITY ASSESSMENT 2 (RA_2)

In step 3, the three dataset-specific interpretations were integrated into a single map following a similar reproducibility assessment (RA_2) procedure. In this second assessment, reproducibility is based on the coincidence, or lack thereof, of interpreted lineaments between different individual datasets within an assigned buffer zone (Buffer_RA_2). Coincident lineaments were assigned a Buffer_RA_2 value of 200 m, 100 m, or 50 m, depending on the maximum distance between individual lineaments. Where coincident lineaments were identified, one of the existing lines was selected or edited to represent that feature; and, where appropriate, a new line was drawn that best captured the merger of individual lineaments, in a process similar to the integration of RA_1 lineaments. The merged lineaments were then assigned a reproducibility value (RA_2) of two or three, depending on whether the feature was identified in any two or all three of the assessed datasets. Whether two or more lineaments exhibited full or partial RA_2 coincidence was determined by the interpreter using a similar process as described for RA_1 in Section 3.2.2. That is, for full coincidence of two or more lineaments, a single integrated feature, attributed accordingly, is carried forward into the final mapped interpretation. Otherwise, a lineament is segmented and attributed according to the partial coincidence of overlapping lineaments, and the partial segments are carried forward into the final mapped interpretation. If a lineament was identified in only one dataset, and thus not a coincident lineament, it received a reproducibility value of one (RA_2 = 1) in the attribute table. The datasets within which each feature has been identified is indicated in the appropriate attribute table field (Geophys, DEM, SAT).

4 FINDINGS

4.1 DESCRIPTION OF LINEAMENTS BY DATASET

4.1.1 SURFICIAL DATASETS (DEM AND SPOT)

Interpreted lineaments from the DEM and SPOT datasets are shown on Figures 8 and 9, respectively. The following paragraphs provide an overview of results from these surface-based interpretations.

A total of 429 lineaments comprise the dataset of merged lineaments (RA_1) identified by the two interpreters from the CDED and SRTM digital elevation data (Figure 8). These lineaments range in length from 229 m to 31.7 km, with a geometric mean length of 1.6 km and a median length of 1.5 km. Twenty nine percent (29%) of these lineaments, a total of 125, were assigned a certainty value of 3, reflecting a lower degree of confidence with the interpretations made from the digital elevation data as compared to the satellite data. This finding may in part be due to the lower resolution of the SRTM data for the eastern portion of the Creighton area where there is poor quality CDED data. It may also reflect the high-degree of certainty associated with identifying small-scale fractures in the large plutons from satellite imagery that are too-small to be resolved by the CDED and SRTM datasets. Certainty values of 2 and 1 were assigned to 232 (54%) and 72 (18%) lineaments, respectively. The reproducibility assessment shows coincidence for 116 lineaments (27%) (RA_1 = 2) and a lack of coincidence for 313 lineaments (73%) (RA_1 = 1). These findings for the DEM data appear to be strongly influenced by the lack of coincidence among shorter lineaments. As with the SPOT data, coincidence increases to around 39% when lineaments shorter than one kilometre in length are excluded from the reproducibility assessment.

Orientation data for the CDED and SRTM lineaments are dominated by a strong northerly trend. Other notable trends include northwesterly and easterly.

The satellite lineament dataset (SPOT) complied from the merger of lineaments identified by the two interpreters yielded a total of 693 lineaments (Figure 9). The length of the lineaments identified on SPOT imagery range from 131 m to 34.1 km, with both a geometric mean and median length of 1.1 km. Of these lineaments, a total of 286 (41%) were assigned the highest level of certainty (Certain = 3). Certainty values of 2 and 1 were assigned to 249 (36%) and 158 (23%) lineaments, respectively. The reproducibility assessment indicates that a total of 553

(80%) lineaments were identified by only one interpreter (RA_1 = 1), while the remaining 140 (20%) were identified by both interpreters (RA_1 = 2). This finding reflects the relatively poor coincidence among lineaments with shorter lengths of less than one kilometre. When these lineaments are excluded from the reproducibility analysis, the coincidence values jump to around 33%. The number of lineaments identified by a single interpreter was comparable for both interpreters suggesting that the differences generally reflect the indistinct nature of the features in the context of the available data quality rather than the experience/competence of the respective interpreters.

SPOT lineaments exhibit a broad range of orientations with prominent trends to the west-northwest, north and east. Also noteworthy are the curvilinear surficial fractures identified within the Annabel Lake pluton which appear to conform to the elliptical shape of the intrusive body.

4.1.2 GEOPHYSICAL DATA

The airborne geophysical data interpretation was able to distinguish features that could be interpreted as brittle lineaments (Figure 10). Aeromagnetic features interpreted to reflect ductile lineaments have been mapped separately and are shown on Figure 11. The ductile lineaments are useful in identifying the penetrative rock fabric, including stratigraphic and foliation traces in the greenstone belts, lithostructural contacts and ductile shear zone fabrics, and magmatic foliation within the plutons. The degree of deformation within the greenstone belts and the "wrapping" of the greenstone stratigraphy around the younger plutons is also clearly visible in the magnetic data. A total of 647 lineaments were interpreted as ductile features. In this report, the ductile lineaments are shown to provide context to our understanding of the tectonic history of the Creighton area, but were not included in the statistical analysis undertaken with the dataset. Therefore the following discussion relates only to those lineaments interpreted by the geophysical expert as brittle lineaments, based on the categorization of these structures as described in Section 1.1.

Brittle lineaments, interpreted from magnetic survey data, total 280 in the Creighton area. The length of these lineaments ranged from 1.0 to 41.3 km, with a geometric mean length of 6.2 km and a median length of 6.3 km. Azimuth data for the geophysical lineaments exhibit a varied distribution of orientations from the north-northwest to the north-northeast and to the east-northeast.

The highest level of certainty (Certainty = 3) was assigned to 232 (83%) of the geophysical faults, while certainty values of two and one were given to 10% and 7% of the faults, respectively. The reproducibility assessment identified coincidence for 270 faults (96%) (RA_1 = 2) and a lack of coincidence for 10 of the interpreted faults (4%) (RA_1 = 1).

4.2 Description and Classification of Integrated Lineament Coincidence (RA_2)

The integrated lineament dataset produced by determining the coincidence of all lineaments interpreted from the CDED and SRTM data, SPOT imagery, and geophysics data is presented on Figures 12 and 13. Figure 12 displays the lineament classification based on the coincidence values determined by Reproducibility Assessment 2 (RA_2). Figure 13 displays the lineament classification based on length. The merged lineaments were classified by length using four length bins: >10 km, 5-10 km, 1-5 km and <1 km. These length bins were defined based on an analysis of the lineament length frequency distributions for the Creighton area.

The merged lineament dataset (RA_2) contains a total of 1108 lineaments that range in length from a minimum of 131 m to a maximum of 41.3 km. The geometric mean length is 1.7 km and the median length is 1.5 km. Lineaments in the >10 km and 5-10 km length bins represent 7% (81) and 11% (122) of the merged lineaments, respectively, while lineaments in the 1-5 km and <1 km length bins represent 45% (499) and 37% (406) of the merged lineaments, respectively. Orientation data from the merged lineament dataset (presented as a length-weighted frequency rose diagram inset on Figures 12 and 13) exhibit a fairly broad distribution toward the north, ranging from northwest to north-northeast. A second broad trend ranges between east-northeast and east-southeast. Note that the broad northerly trend may, in part, be influenced by the easterly trend of the flight lines for the geophysical data acquisition.

The reproducibility assessment required some lineaments to be broken into several line segments to which different reproducibility values were assigned. This is because lineaments may be coincident for just one segment and not for the entire length. For this reason, the total number of line segments (1,262) analyzed in the reproducibility assessment is larger than the total number of lineaments in the integrated dataset (1,108). Results from the reproducibility assessment (RA_2) for this dataset show 1,044 lineament segments (83%) that lack a coincident lineament from the other datasets and thus were assigned a value of 1. A total of 178 lineament segments (14%) were coincident with a lineament from one other dataset (RA_2 = 2) and 40 lineament segments (3%) were identified and coincident on all three datasets (RA_2 = 3). Several factors may contribute to the low degree of coincidence observed among the different datasets in this area. The lack of coincidence between surficial lineaments observed in the eastern portion of the

Creighton area likely reflects the lower resolution of the SRTM data used here where there is poor quality CDED data. It is also noted that numerous small fractures in the exposed plutons that were identified and mapped from the SPOT imagery were too small to be resolved by the digital elevation data from either CDED or SRTM. Another notable observation is that the geophysics identified several strong northeast to east trends that were not mapped from the surficial datasets.

4.3 DESCRIPTION OF LINEAMENTS BY PLUTON IN THE CREIGHTON AREA

As described in Section 2.2, the bedrock geology of the Creighton area features metasedimentary and metavolcanic rocks associated with greenstone belts that are separated by several large plutonic bodies (Figures 3 and 14). Among these plutons are the Annabel Lake pluton, Reynard Lake pluton, and Phantom-Boot Lake pluton. Collectively, these plutons account for a total of 622 (35%) lineaments. The following discussion describes the dominant interpreted lineament orientations for each of these rock bodies.

The Annabel Lake pluton exhibited 321 total lineaments over an area of 89 km^2 and a high lineament density, particularly toward the eastern end where an absence of surfical cover exposes the bedrock. Within the Annabel Lake pluton, the mapped lineaments have a geometric mean length of 1.6 km and a median length of 1.3 km. Azimuths of the lineaments mapped over the Annabel Lake pluton were weighted by length and plotted on a rose diagram. The results show a uniformly broad distribution of orientations, with a notable low frequency of northeasterly oriented features (Figure 14).

A total of 205 lineaments were mapped over the Reynard Lake pluton, which covers an area of 90 km^2. Lineaments over the Reynard Lake pluton have a geometric mean length of 2.6 km and a median length of 2.3 km. Orientations of these lineaments were weighted by length and plotted on a rose diagram, which shows a wide distribution of orientations with three broad trends; one to the west-northwest, one ranging between northwest and north-northeast and to the east-northeast (Figure 14).

The Phantom-Boot Lake pluton covers an area of approximately 14 km^2 from which a total of only 60 lineaments were mapped. The length of these lineaments have a geometric mean of 1.0 km and a median of 0.7 km. Azimuth data for these lineaments show a slightly different distribution than the two larger plutons, with prominent orientations ranging predominantly between north and east. A secondary northwest trend of interpreted lineaments is also noted (Figure 14).

In summary, it appears that in general a similar broadly distributed brittle lineament pattern overprints all three of these plutons in the Creighton area (Figure 14).

5 DISCUSSION

The following sections are provided to discuss the results of the lineament interpretation in terms of lineament density, reproducibility, coincidence, lineament length, the relationship between mapped faults and interpreted lineaments, and the relative age relationships of the interpreted lineaments.

5.1 LINEAMENT DENSITY

Lineament density refers to the length of lineaments per unit area. The distribution of lineament densities differs markedly across the Creighton area and appears to be closely related to bedrock elevation and the extent of overburden cover. The highest lineament densities are observed in the northeast of the Creighton area where there are higher elevations and less overburden, while the lowest densities are found in the south and the east where there are extensive lakes and greater surficial cover. Lineament density was calculated using the line density method described in ESRI ArcGIS software, which determines the length of lineaments within a moving circular window (km/km^2). A radius of 1.25 km was used for the moving circular window, based on the repository footprint size and a 50 m cell size.

An understanding of the distribution and thickness of overburden cover within the Creighton area is essential for interpreting the lineament results, particularly for interpreting information on length and density of surficial lineaments. Thick drift deposits are able to mask the surface expression of lineaments. In areas of thick and extensive overburden, major structures could exist completely undetectable in the satellite imagery and digital elevation data, particularly if these areas also contain large lakes, such as Amisk Lake. The interpretation of geophysical lineaments, on the other hand, is less affected by surficial cover. The variability of the density of geophysical lineaments is influenced by the resolution of the available magnetic data more than the presence or absence of overburden cover.

The lineament density is, in general, quite low across the entire Creighton area ranging between about 2 and 10 km/km^2. The lowest lineament densities are observed in the southwest, where Amisk Lake obscures the bedrock structure. Low lineament densities are also observed in wetland areas over the Phantom-Boot Lake pluton and the wetlands over the western parts of the Annabel Lake and Reynard Lake plutons. The highest lineament densities are observed in the exposed bedrock of the Annabel Lake pluton. Here, as with other exposed intrusive rocks from the Reynard Lake and Phantom-Boot Lake plutons, there are numerous, small-scale fractures that were mapped and that contribute to the high lineament density.

5.2 Reproducibility and coincidence

Reproducibility values assigned to the lineaments provide a measure of the significance of the bedrock structures expressed in the different datasets. The approach used to assign reproducibility values involved checking whether lineament interpretations from different interpreters (RA_1), and from different datasets (RA_2), were coincident within a specified buffer zone radius. Reproducibility and coincidence values are discussed in detail in Sections 4.1 and 4.2.

The findings from the reproducibility assessment indicate that approximately 20 to 25% of surficial lineaments from the same dataset were identified by both interpreters (see Figures 8 and 9). Importantly, longer lineaments with higher certainty values were identified more often by both interpreters. The reproducibility assessment of the geophysical lineaments shows that about 96% were identified by both interpreters (Figure 10). As with the surficial lineaments, longer geophysical lineaments with higher certainty values were also recognized more often by both interpreters (RA_1=2).

Coincidence between features identified in the various datasets was evaluated for the second Reproducibility Assessment (RA_2). The surficial lineaments interpreted from DEM and SPOT show coincidence at 14%. This is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. For example, a lineament drawn along a stream channel shown on the satellite imagery is expected to be coincident with a lineament that captures the trend of the associated topographic valley expressed in the digital elevation data. Notable exceptions exist where features mapped on the higher resolution satellite imagery were not identified on the lower resolution digital elevation data. In particular, numerous, small-scale fractures observed in the bedrock on the satellite imagery were not resolved by digital elevation data, which resulted in considerable lack of reproducibility.

Of the total set of merged lineaments carried forward in RA_2, only 9% showed coincidence between a surficial (DEM or SPOT) and geophysical lineament. When only the set of geophysical lineaments is considered a total of 26% were coincident with an interpreted surficial lineament. These coincidence values between surficial and geophysical lineaments are not unexpected, and may be the result of various factors, such as: deep structures that are identified in geophysics may not have a surface expression; surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and/or the geometry of the feature (e.g., dipping versus vertical). All these may be further constrained by the resolution of the datasets.

For these reasons it is necessary to objectively analyze the results of the RA_2 assessment with the understanding that RA_2 = 1 does not necessarily imply a low degree of confidence that the specified lineament represents a true geological feature (i.e., a fracture). The true nature of the interpreted features will need to be investigated further during subsequent stages of the site evaluation process, if the community is selected by the NWMO, and remains interested in continuing with the site selection process.

Regardless of the degree of coincidence, the observed overlap in dominant lineament orientation between all datasets (see insets on Figures 8, 9 and 10) suggests that all datasets are identifying the same regional sets of structures. Among the lineaments with the best reproducibility are those associated with major shear zones, such as the Annabel Lake shear zone, the West Arm shear zone, the Mosher Lake shear zone, and the Comeback Bay shear zone (Figure 3).

5.3 LINEAMENT LENGTH

Figure 13 shows the interpreted lineaments classified by lineament length. Four lineament length bins (0-1 km, 1-5 km, 5-10 km, >10 km) were used for this analysis and a length weighted frequency rose diagram indicates the dominant lineament orientations (inset of Figure 13). Three prominent lineament orientation sets (N, WNW, and ENE) can be recognized in the length-weighted dataset.

There is no information available on the depth extent into the bedrock of the lineaments interpreted for the Creighton area. In the absence of available information, the interpreted length can be used as a proxy for the depth extent of the identified structures. A preliminary assumption may be that the longer interpreted lineaments in the Creighton area may extend to greater depths than the shorter interpreted lineaments.

As discussed in Section 4.2, longer interpreted lineaments generally have higher certainty and reproducibility values. Although the existence of interpreted lineaments would need to be confirmed through field observations, certainty and reproducibility values provide a preliminary indication of the higher confidence that the longer features identified are related to bedrock structures.

5.4 FAULT AND LINEAMENT RELATIONSHIPS

As discussed above in Section 2.5.6, there are a number of mapped structural features in the Creighton area with established relative age relationships. The known mapped faults and shear zones include the east-trending Annabel Lake shear zone, the east- to south-trending West Arm shear zone and Mosher Lake shear zone, and the south-trending Comeback Bay Shear zone. Based on the compilation of interpreted lineaments orientations shown in the inset of Figures 12 and 13, the lineament sets identified herein appear to correspond in orientation to the major shear zones.

The principle neotectonic stress orientation in central North America is generally oriented approximately east-northeasterly (063º ± 28º; Heidbach et al., 2009), although anomalous stress orientations have also been reported in the mid-continent that include a 90º change in azimuth of the maximum compressive stress axis (Brown et al., 1995) and a north-south maximum horizontal compressive stress (Haimson, 1990). Other potential complicating factors involved in characterizing crustal stresses, include, the effect of shear stress by mantle flow at the base of the lithosphere (Bokelmann, 2002; Bokelmann and Silver, 2002), the degree of coupling between the North American plate and the underlying mantle (Forte et al., 2010), and the influence of the thick lithospheric mantle root under the Canadian Shield. Acknowledging these factors, it is still useful to attempt a preliminary comparison of the regional east-northeasterly neotectonic stress orientation with the orientation of each lineament set identified herein.

As discussed above, a broad ranging brittle lineament pattern overprints the plutons in the Creighton area and both northwest to north-northeast (northerly) and east-northeast to east-southeast (easterly) oriented sets are recognized. These features were formed by Precambrian paleostresses, potentially modified by Phanerozoic paleostresses (e.g., Table 1), and are now subjected to the conditions of the modern stress regime. Therefore under the current east-northeasterly-oriented regional neotectonic stress regime, the most northwesterly of the north-trending set would preferentially remain closed, the most northerly of the east-trending set would preferentially open as tension fractures, and the remaining lineaments would be preferentially oriented for shear re-activation.

5.5 Relative age relationships

The chronology of tectonic events that occurred during the Trans-Hudson Orogen, outlined in Section 2.3, provides a framework for understanding the structural history and for constraining the relative age relationships of the interpreted bedrock lineaments in the Creighton area. All of the lineaments identified in the Creighton area reflect initial formation during Proterozoic deformational events with later reactivation that may have continued into the Paleozoic Era (e.g., Table 1). It is generally accepted that there is a relationship between the orientation of lineament sets and relative age associated with deformational events. The relative age of the lineament sets can also be established on the basis of cross-cutting relationships. This section integrates the observed lineaments with the structural history of the area, based on the available information. This interpretation, which may be refined as more information becomes available, was used at this stage to assist with the identification of potentially suitable siting areas within the plutons (Golder, 2013).

Based on the available literature of the structural history of the Creighton area and observations of the orientation of lineament sets, the relative age of the mapped lineaments can be related to two distinct regional composite deformation episodes, one related to ductile to brittle-ductile shear zone activation (D_3-D_4) and one brittle (D_5) (Figure 3.18 in Golder, 2013). The major shear zones were developed during the regional D_3 deformation event and initially reactivated during the D_4 event. It is likely that these D_3-D_4 structures also had a post-D_4 history of brittle re-activation during the later faulting episodes described below. They are curvilinear features, reflecting their ductile-brittle nature and have orientations that generally range from east-west to southeast. As mentioned above, coincident lineaments from all three independent datasets (geophysical and surficial lineaments with RA_2 = 3) are noted for all of the major shear zones over significant portions of their mapped length. As such these lineaments can be classified, with some degree of confidence, as composite D_3-D_4 structures.

Numerous short lineaments within the plutons can be correlated to the shear zones based on a similar orientation. The visibility of these features is strongly influenced by overburden cover. They are responsible for the high lineament density in areas with very good bedrock exposure. They also have a low degree of coincidence between the SPOT, DEM and aeromagnetic datasets. These short lineaments may be related to D_3-D_4 but are not interpreted to be features that extend to depths greater than 100 m. These short, curvilinear lineaments have been interpreted as brittle-ductile and may be associated with internal foliation, compositional variations or possibly the surface expression of the shallow (<100 m deep) fracture system typical of the Canadian Shield.

The major D_3-D_4 shear zones are crosscut by younger D_5-D_6 faults. This is best shown in the Creighton area by the Ross Lake fault which is interpreted to have formed during D_5 (Ansdell and Kyser, 1990; Fedorowich et al., 1993; NATMAP, 1998; Saskatchewan Energy and Resources, 2010) and, as a part of the Tabbernor fault system to have been reactivated during D_6. This cross-cutting relationship is clearly evident to the northeast of the Annabel Lake pluton, near Harnell Lake, where the Ross Lake fault offsets D_3 and D_4 features. The Ross Lake fault is matched by a lineament with coincidence between all three datasets (RA_2= 3). The Embury Lake flexure, and the north-northeast to north-northwest trending splays related to the Ross Lake fault, are all identified by surficial and geophysical lineaments that have coincidence between at least two datasets (RA_2 =2) and are all longer than 10 km. A number of long north-northeast to north-northwest oriented lineaments have the same orientation as mapped brittle faults.

The northeast-trending lineaments are primarily concentrated in the Flin Flon greenstone belt and are coincident with mapped faults in the Creighton area. Complex faulting in the Creighton area makes the relative age of these fault structures uncertain, although this series belongs to the D_5-D_6 event (Galley et al., 1991). Byers (1962) interprets the northeast trending faults to also be a component of the Ross Lake fault system. Within the greenstone belt, for example immediately east of the Phantom-Boot Lake pluton, some of these relatively short faults are coincident with surficial lineaments observed to cross-cut the Flin Flon Lake fault, suggesting that they are the youngest mapped faults in the area.

Prominent north-northwest to north-northeast and northeast lineament trends noted in the aeromagnetic dataset correspond to the D_5-D_6 faults. In addition, east-west lineament trends noted in the aeromagnetic dataset, corresponding to the D_3 shear zones. The north-northwest to north-northeast trending faults are the most widespread and appear to include the southern parts of the Comeback Bay and Mosher Lake shear zones. These lineaments are well represented in the plutons of interest, although no faults have been noted to extend significantly into these units in the available mapping. A number of long geophysical lineaments have a similar orientation as the northeast-trending faults. These features do not coincide with any of the surficial lineaments and coincidence between these lineaments with mapped faults of the same orientation appears low. Several long northeast-trending geophysical lineaments traverse the plutons, however these features have similarly not been noted in the available mapping of the plutons. As such, the importance of these long geophysical lineaments is less certain.

The surficial lineaments display three strong trends that correspond to the mapped D_5-D_6 faults and major shear zones in the area. The rose diagram for the SPOT data shows two strong orientations to the northeast and the general east-west trend, while the rose diagram for the DEM data show a dominant trend to the north-northwest through north-northeast. The north-northwest to north-northeast trending lineaments are interpreted to correspond to the similarly oriented sinistral faults. The northeast oriented lineaments are interpreted to correspond to similarly oriented dextral faults. The dominant east-southeasterly trend displayed by the SPOT dataset largely corresponds to the D_3 shear zones adjacent to the Annabel and Reynard Lake plutons as well as many of the short lineaments observed in the plutons.

In summary, the most important mapped features, with established age relationships, have been identified through the lineament analysis. They are defined by longer >10 km lineaments with greater coincidence amongst datasets. This allows the known age relationships to be extended to the other identified lineaments with similar orientations. These mapped features are well characterized at surface and may extend to repository depth. All three datasets used to map lineaments identified these features (RA_2 = 3).

6 SUMMARY

This report documents the source data, workflow and results from a lineament interpretation of digital datasets, including surficial (satellite imagery, digital elevation) and geophysical (aeromagnetic) datasets, for the Creighton area in east-central Saskatchewan. The lineament analysis provides an interpretation of the location and orientation of possible individual fractures or fracture zones and helps to evaluate their relative timing relationships within the context of the regional geological setting. The three-step process involved a workflow that was designed to address the issues of subjectivity and reproducibility.

Lineaments were mapped from multiple, readily-available datasets that include digital elevation models (CDED and SRTM), satellite imagery (SPOT), and geophysical survey data. The total number of lineaments interpreted from these data sources were 429, 693, and 280, respectively. The distribution of lineaments in the Creighton area reflects the bedrock structure, resolution of the datasets used, and surficial cover. Surface lineament density, as demonstrated in this study, is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. Lineament density was observed to be highest in the eastern part of the Annabel Lake pluton and the central part of the Reynard Lake pluton, where exposed bedrock revealed numerous fractures. The lowest lineament densities were observed from low lying areas covered by overburden, lakes, and wetlands, including the western sections of the Annabel Lake and Reynard Lake plutons.

In terms of reproducibility, longer interpreted lineaments generally have higher certainty and reproducibility values. Reproducibility was highest for the major shear zones, which were expressed in each of the datasets. Comparison between various datasets (RA_2), indicates that the highest level of coincidence is between surficial lineaments interpreted from DEM and SPOT. This is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. The low coincidence between surficial and geophysical lineaments may be the result of various factors: deep structures identified in geophysics may not have a surface expression; surficial features may not extend to great depth; structural features may not possess a magnetic susceptibility contrast with the host rock; surface expressions of lineaments may be masked by the presence of overburden; and the geometry of the feature (e.g., dipping versus vertical). These factors are further constrained by the differing resolution of the various datasets.

The orientations observed for the combined set of brittle lineaments include two broad trends ranging from northwest to north-northeast, and east-northeast to east-southeast.

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REPORT SIGNATURE PAGE

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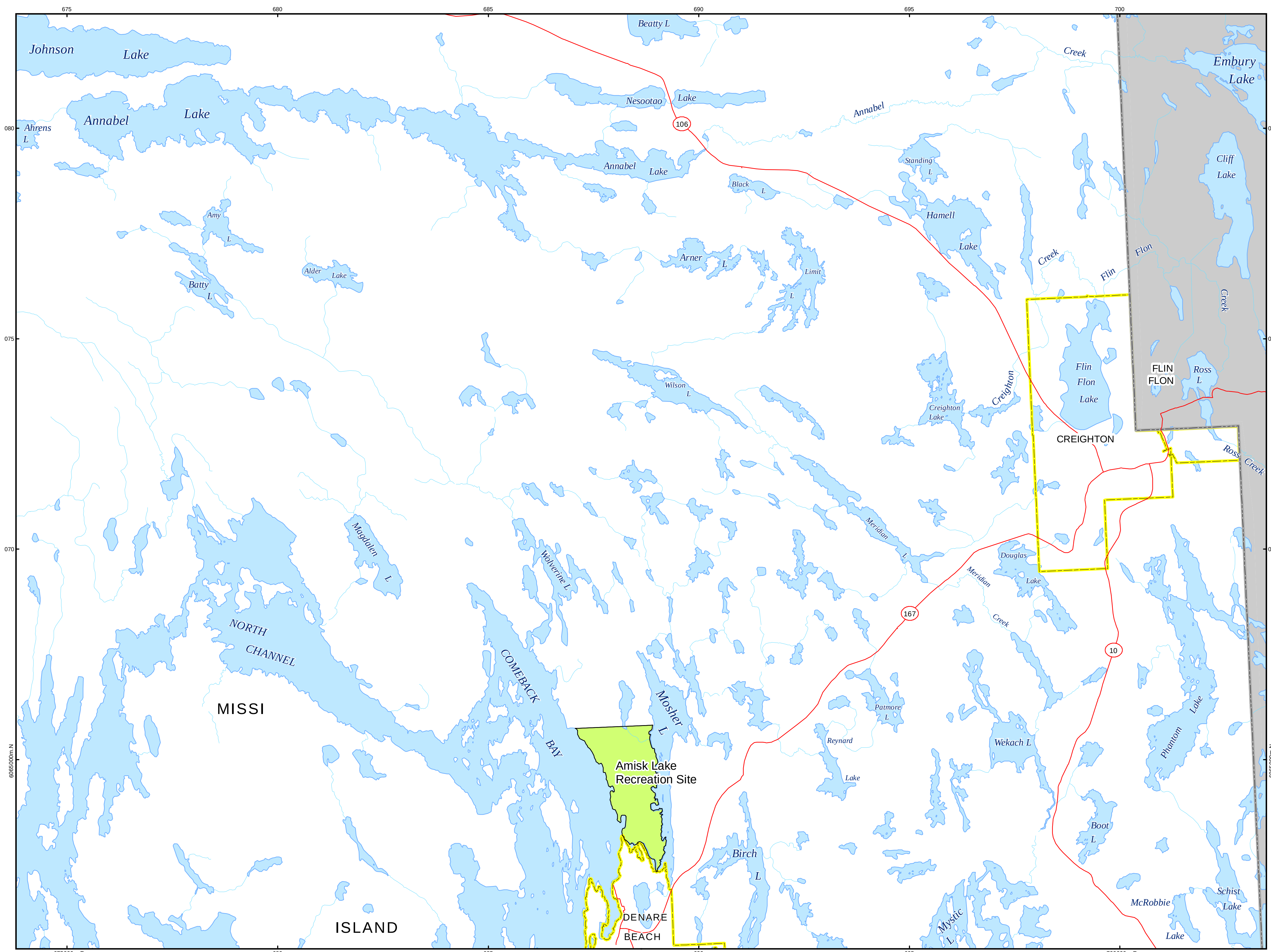
FIGURES



LEGEND

- Main road
- Provincial border
- Urban municipality
- Waterbody
- Watercourse
- Recreation site

Data sources:
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

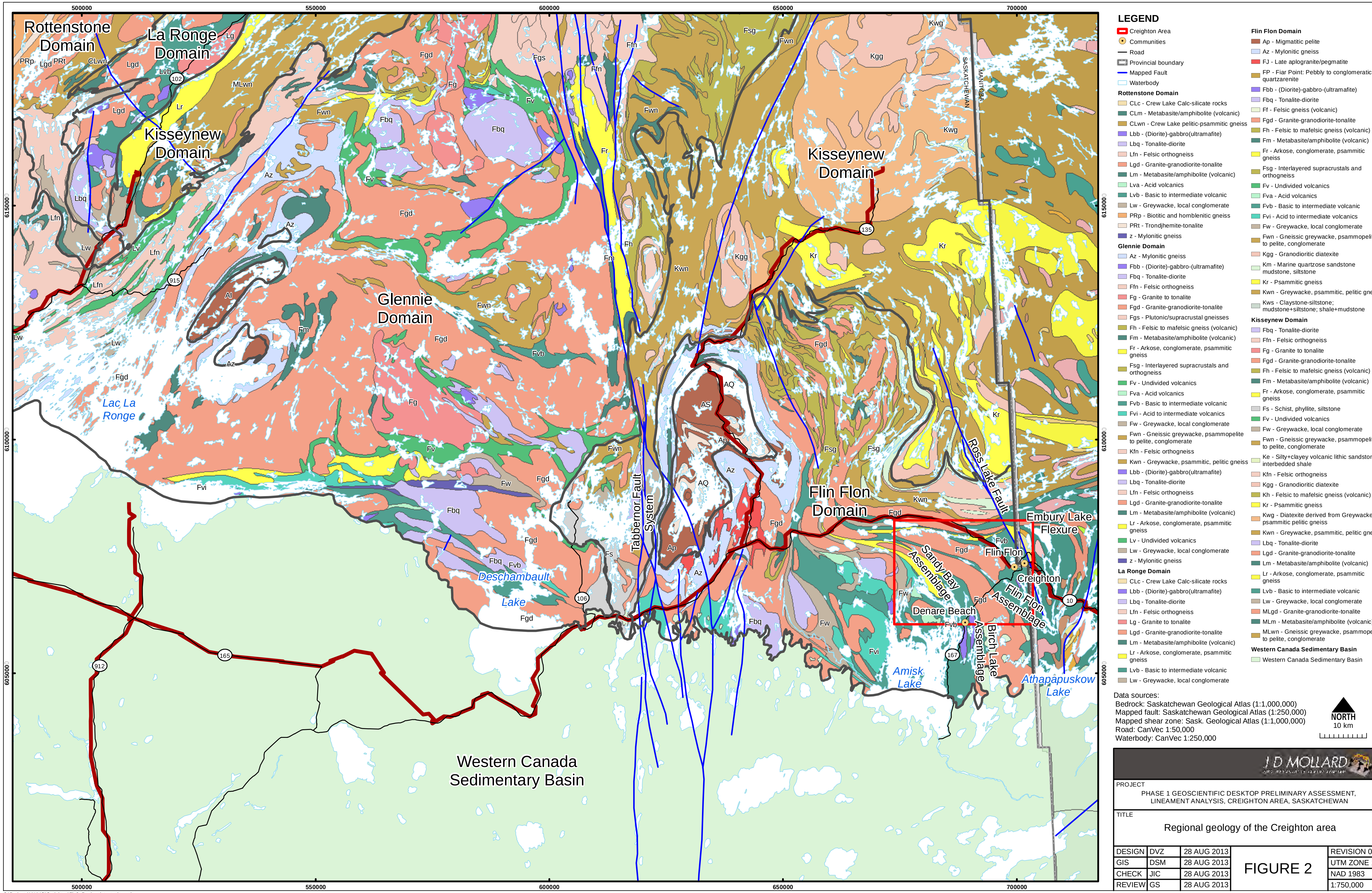
2 km

J D MOLLARD

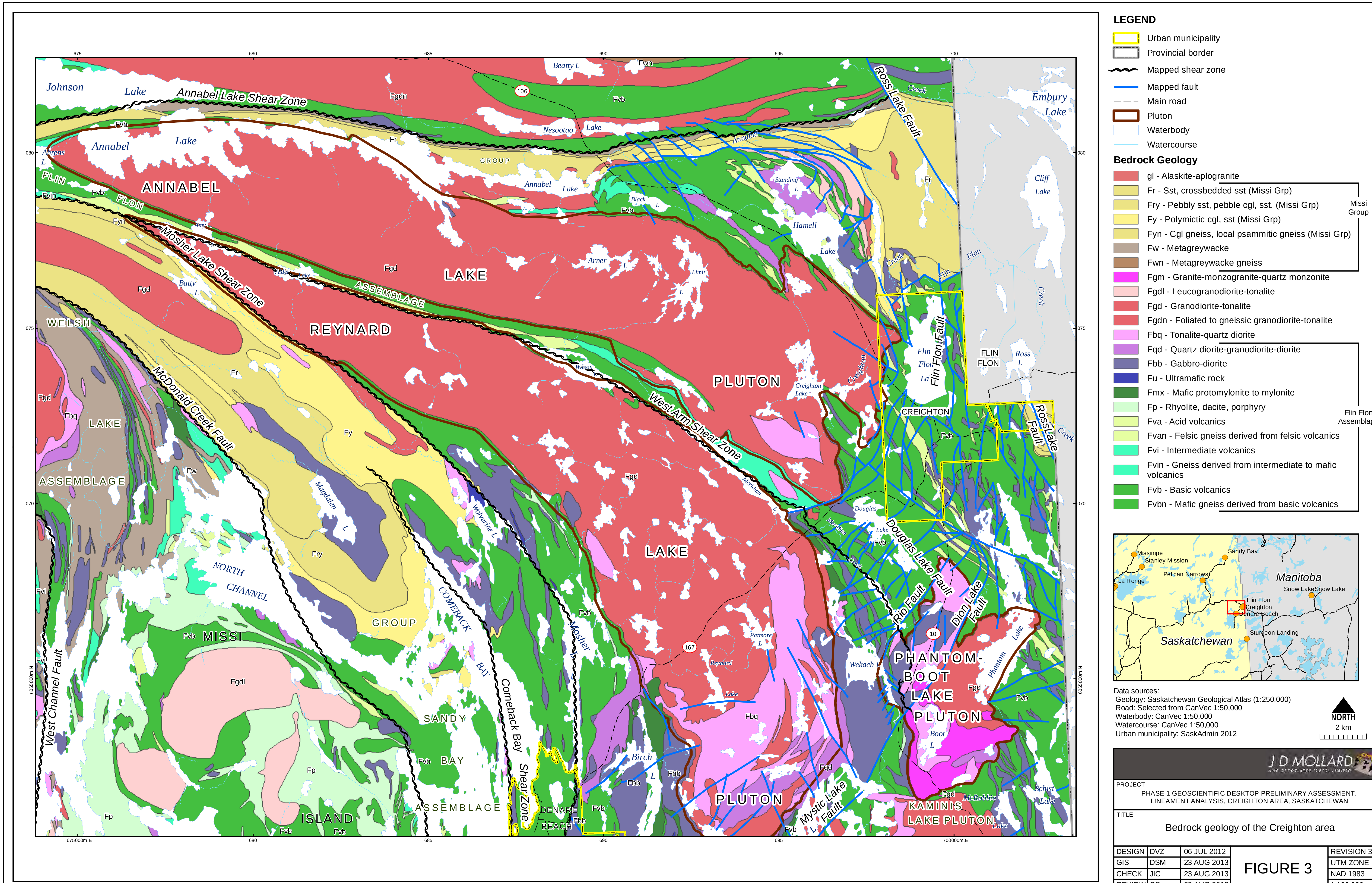
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
Creighton and surrounding area

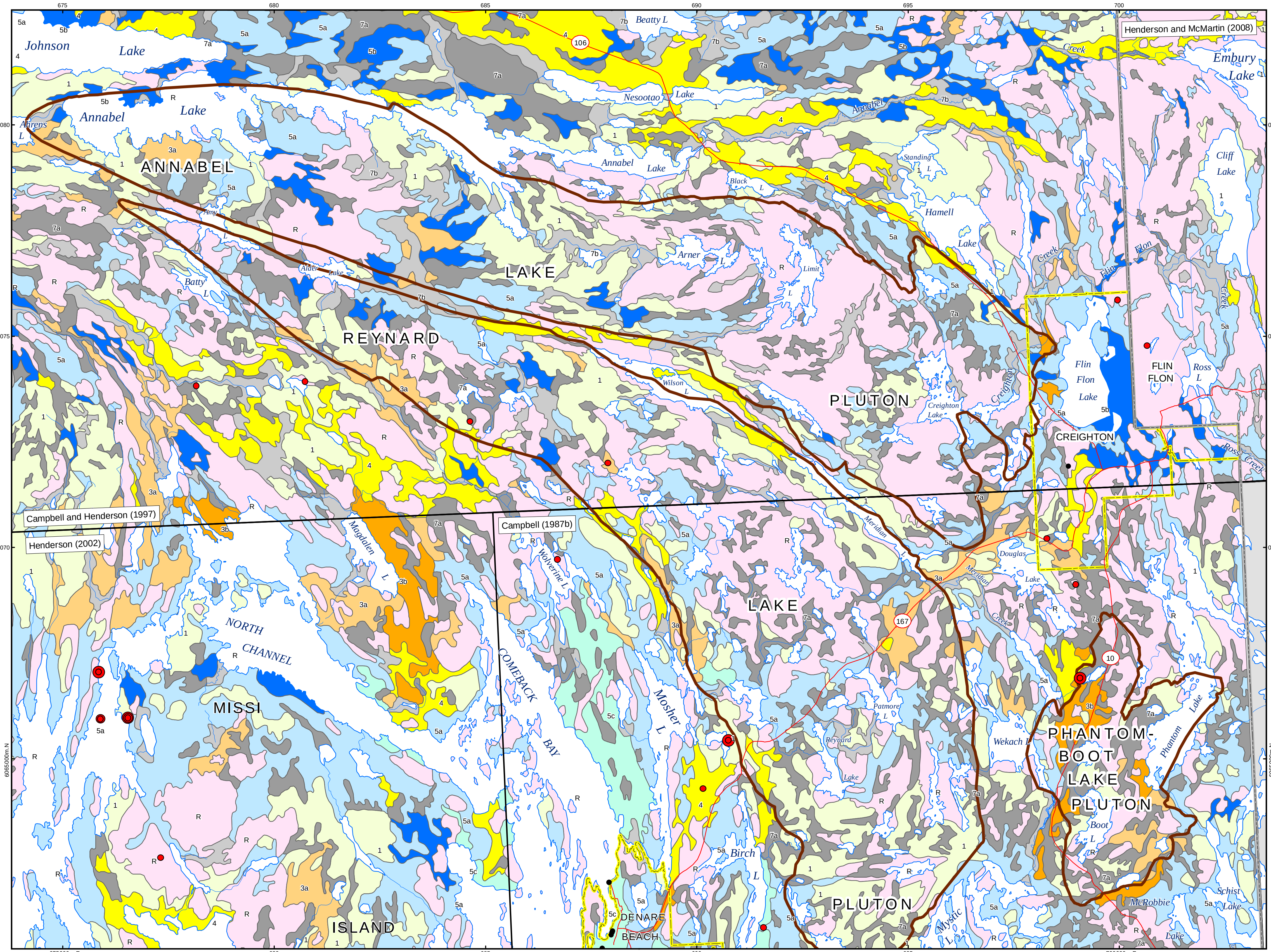
DESIGN	DVZ	06 JUL 2012	FIGURE 1	REVISION 3
GIS	DSM	07 NOV 2013		UTM ZONE 13
CHECK	JIC	07 NOV 2013		NAD 1983
REVIEW	GS	07 NOV 2013		1:100,000



Rottenstone Domain
La Ronge Domain
Kisseynew Domain
Glennie Domain
Kisseynew Domain
Flin Flon Domain
Western Canada Sedimentary Basin
Lac La Ronge
Deschambault Lake
Amisk Lake
Athapapuskow Lake
Tabbernor Fault System
Ross Lake Fault
Embury Lake Flexure
Sandy Bay Assemblage
Flin Flon Assemblage
Birch Lake Assemblage
Flin Flon
Creighton
Denare Beach
SASKATCHEWAN
MANITOBA
500000
550000
600000
650000
700000
605000
610000
615000
LEGEND
Creighton Area
Communities
Road
Provincial boundary
Mapped Fault
Waterbody
Rottenstone Domain
CLc - Crew Lake Calc-silicate rocks
CLm - Metabasite/amphibolite (volcanic)
CLwn - Crew Lake pelitic-psammitic gneiss
Lbb - (Diorite)-gabbro(ultramafite)
Lbq - Tonalite-diorite
Lfn - Felsic orthogneiss
Lgd - Granite-granodiorite-tonalite
Lm - Metabasite/amphibolite (volcanic)
Lva - Acid volcanics
Lvb - Basic to intermediate volcanic
Lw - Greywacke, local conglomerate
PRp - Biotitic and hornblenitic gneiss
PRt - Trondjhemite-tonalite
z - Mylonitic gneiss
Glennie Domain
Az - Mylonitic gneiss
Fbb - (Diorite)-gabbro(ultramafite)
Fbq - Tonalite-diorite
Ffn - Felsic orthogneiss
Fg - Granite to tonalite
Fgd - Granite-granodiorite-tonalite
Fgs - Plutonic/supracrustal gneisses
Fh - Felsic to mafelsic gneiss (volcanic)
Fm - Metabasite/amphibolite (volcanic)
Fr - Arkose, conglomerate, psammitic gneiss
Fsg - Interlayered supracrustals and orthogneiss
Fv - Undivided volcanics
Fva - Acid volcanics
Fvb - Basic to intermediate volcanic
Fvi - Acid to intermediate volcanics
Fw - Greywacke, local conglomerate
Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
Kfn - Felsic orthogneiss
Kwn - Greywacke, psammitic, pelitic gneiss
Lbb - (Diorite)-gabbro(ultramafite)
Lbq - Tonalite-diorite
Lfn - Felsic orthogneiss
Lgd - Granite-granodiorite-tonalite
Lm - Metabasite/amphibolite (volcanic)
Lr - Arkose, conglomerate, psammitic gneiss
Lv - Undivided volcanics
Lw - Greywacke, local conglomerate
z - Mylonitic gneiss
La Ronge Domain
CLc - Crew Lake Calc-silicate rocks
Lbb - (Diorite)-gabbro(ultramafite)
Lbq - Tonalite-diorite
Lfn - Felsic orthogneiss
Lg - Granite to tonalite
Lgd - Granite-granodiorite-tonalite
Lm - Metabasite/amphibolite (volcanic)
Lr - Arkose, conglomerate, psammitic gneiss
Lvb - Basic to intermediate volcanic
Lw - Greywacke, local conglomerate
Flin Flon Domain
Ap - Migmatitic pelite
Az - Mylonitic gneiss
FJ - Late aplogranite/pegmatite
FP - Fiar Point: Pebbly to conglomeratic quartzarenite
Fbb - (Diorite)-gabbro-(ultramafite)
Fbq - Tonalite-diorite
Ff - Felsic gneiss (volcanic)
Fgd - Granite-granodiorite-tonalite
Fh - Felsic to mafelsic gneiss (volcanic)
Fm - Metabasite/amphibolite (volcanic)
Fr - Arkose, conglomerate, psammitic gneiss
Fsg - Interlayered supracrustals and orthogneiss
Fv - Undivided volcanics
Fva - Acid volcanics
Fvb - Basic to intermediate volcanic
Fvi - Acid to intermediate volcanics
Fw - Greywacke, local conglomerate
Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
Kgg - Granodioritic diatexite
Km - Marine quartzose sandstone mudstone, siltstone
Kr - Psammitic gneiss
Kwn - Greywacke, psammitic, pelitic gneiss
Kws - Claystone-siltstone; mudstone+siltstone; shale+mudstone
Kisseynew Domain
Fbq - Tonalite-diorite
Ffn - Felsic orthogneiss
Fg - Granite to tonalite
Fgd - Granite-granodiorite-tonalite
Fh - Felsic to mafelsic gneiss (volcanic)
Fm - Metabasite/amphibolite (volcanic)
Fr - Arkose, conglomerate, psammitic gneiss
Fs - Schist, phyllite, siltstone
Fv - Undivided volcanics
Fw - Greywacke, local conglomerate
Fwn - Gneissic greywacke, psammopelite to pelite, conglomerate
Ke - Silty+clayey volcanic lithic sandstone, interbedded shale
Kfn - Felsic orthogneiss
Kgg - Granodioritic diatexite
Kh - Felsic to mafelsic gneiss (volcanic)
Kr - Psammitic gneiss
Kwg - Diatexite derived from Greywacke, psammitic pelitic gneiss
Kwn - Greywacke, psammitic, pelitic gneiss
Lbq - Tonalite-diorite
Lgd - Granite-granodiorite-tonalite
Lm - Metabasite/amphibolite (volcanic)
Lr - Arkose, conglomerate, psammitic gneiss
Lvb - Basic to intermediate volcanic
Lw - Greywacke, local conglomerate
MLgd - Granite-granodiorite-tonalite
MLm - Metabasite/amphibolite (volcanic)
MLwn - Gneissic greywacke, psammopelite to pelite, conglomerate
Western Canada Sedimentary Basin
Western Canada Sedimentary Basin
Data sources:
Bedrock: Saskatchewan Geological Atlas (1:1,000,000)
Mapped fault: Saskatchewan Geological Atlas (1:250,000)
Mapped shear zone: Sask. Geological Atlas (1:1,000,000)
Road: CanVec 1:50,000
Waterbody: CanVec 1:250,000
NORTH
10 km
J D MOLLARD
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN
TITLE
Regional geology of the Creighton area
DESIGN DVZ 28 AUG 2013
GIS DSM 28 AUG 2013
CHECK JIC 28 AUG 2013
REVIEW GS 28 AUG 2013
FIGURE 2
REVISION 0
UTM ZONE 13
NAD 1983
1:750,000
C:\Projects\NWMO\Creighton\Fig2_Regional_tectonic.mxd



LEGEND
Urban municipality
Provincial border
Mapped shear zone
Mapped fault
Main road
Pluton
Waterbody
Watercourse
Bedrock Geology
gl - Alaskite-aplogranite
Fr - Sst, crossbedded sst (Missi Grp)
Fry - Pebbly sst, pebble cgl, sst. (Missi Grp)
Fy - Polymictic cgl, sst (Missi Grp)
Fyn - Cgl gneiss, local psammitic gneiss (Missi Grp)
Fw - Metagreywacke
Fwn - Metagreywacke gneiss
Missi Group
Fgm - Granite-monzogranite-quartz monzonite
Fgdl - Leucogranodiorite-tonalite
Fgd - Granodiorite-tonalite
Fgdn - Foliated to gneissic granodiorite-tonalite
Fbq - Tonalite-quartz diorite
Fqd - Quartz diorite-granodiorite-diorite
Fbb - Gabbro-diorite
Fu - Ultramafic rock
Fmx - Mafic protomylonite to mylonite
Fp - Rhyolite, dacite, porphyry
Fva - Acid volcanics
Fvan - Felsic gneiss derived from felsic volcanics
Fvi - Intermediate volcanics
Fvin - Gneiss derived from intermediate to mafic volcanics
Fvb - Basic volcanics
Fvbn - Mafic gneiss derived from basic volcanics
Flin Flon Assemblage
Annabel Lake Shear Zone
Mosher Lake Shear Zone
West Arm Shear Zone
McDonald Creek Fault
West Channel Fault
Comeback Bay Shear Zone
Ross Lake Fault
Flin Flon Fault
Douglas Lake Fault
Rio Fault
Dion Lake Fault
Mystic Lake Fault
ANNABEL LAKE REYNARD PLUTON
LAKE PLUTON
PHANTOM-BOOT LAKE PLUTON
KAMINIS LAKE PLUTON
WELSH LAKE ASSEMBLAGE
FLIN FLON ASSEMBLAGE
MISSI GROUP
MISSI ISLAND
NORTH CHANNEL
SANDY BAY ASSEMBLAGE
FLIN FLON
CREIGHTON
DENARE BEACH
Johnson Lake
Annabel Lake
Beatty L
Nesootao Lake
Embury Lake
Cliff Lake
Standing L
Hamell Lake
Black L
Arner L
Limit L
Batty L
Creighton Lake
Wilson
Douglas Lake
Patmore L
Reynard Lake
Wekach L
Boot L
Phantom Lake
McRobbie
Schist Lake
Birch L
Magdalen L
Wolverine L
Ahrens L
Manitoba
Saskatchewan
Missinipe
Stanley Mission
Sandy Bay
Pelican Narrows
La Ronge
Snow Lake
Flin Flon
Creighton
Denare Beach
Sturgeon Landing
Data sources:
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012
NORTH
2 km
J D MOLLARD
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN
TITLE
Bedrock geology of the Creighton area
DESIGN DVZ 06 JUL 2012
GIS DSM 23 AUG 2013
CHECK JIC 23 AUG 2013
REVIEW GS 23 AUG 2013
FIGURE 3
REVISION 3
UTM ZONE 13
NAD 1983
1:100,000



LEGEND

- Pluton
- Main road
- Provincial border
- Surficial geology map
- Waterbody
- Urban municipality
- Watercourse
- Pluton

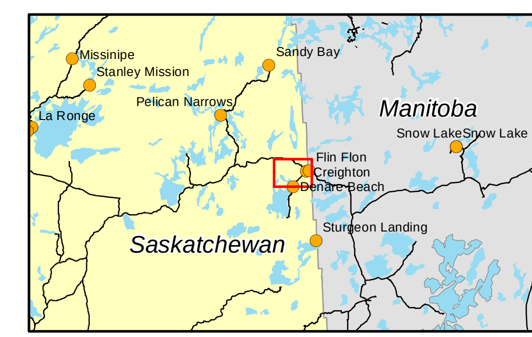
Quaternary geology

- 7b - Fen peat
- 7a - Bog peat
- 5c - Glaciolacustrine nearshore
- 5b - Glaciolacustrine offshore blanket
- 5a - Glaciolacustrine offshore veneer
- 3c - Glaciofluvial subaqueous outwash
- 3b - Glaciofluvial ice-contact
- 3a - Sand and gravel of undetermined origin
- 1 - Till veneer
- R - Bedrock
- Water well

Drill hole

Depth to bedrock (m)

- 0.0 - 10.0
- 10.1 - 20.0
- 20.1 - 71.3



Data sources:
Pluton: After Sask Geological Atlas (1:250,000)
Geology: 1:50,000 scale geology as referenced
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

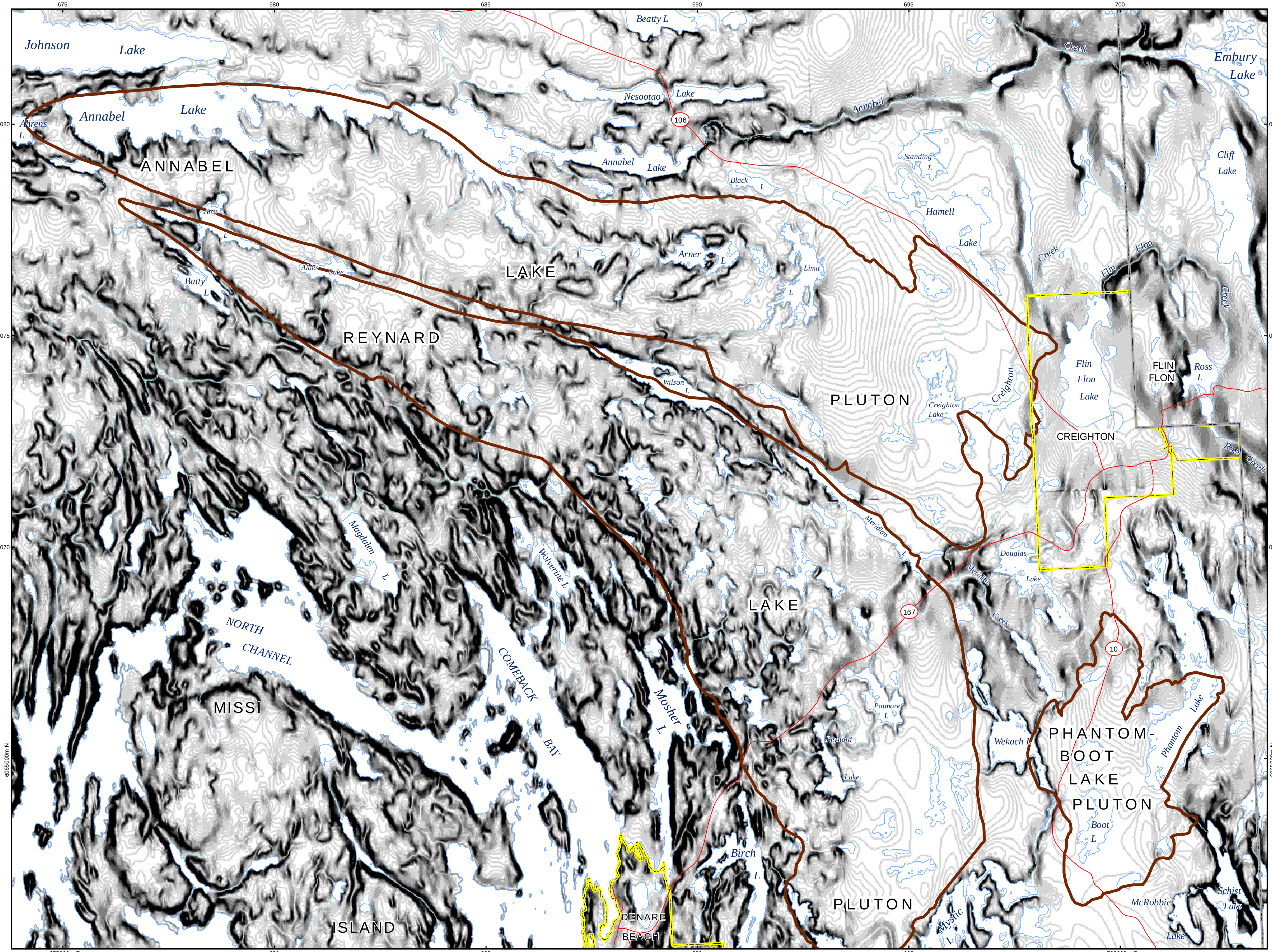
NORTH
2 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
Surficial geology of the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 4	REVISION 3
GIS	DVZ	08 AUG 2013		UTM ZONE 13
CHECK	LAP\AM	08 AUG 2013		NAD 1983
REVIEW	GS	08 AUG 2013		1:100,000

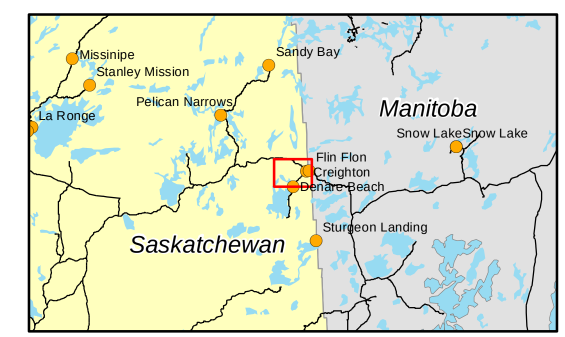


LEGEND

- Main road
- Provincial border
- Urban municipality
- Pluton
- Waterbody
- Watercourse

Slope (°)

- 0 - 0.7
- 0.8 - 1.8
- 1.9 - 2.8
- 2.9 - 3.8
- 3.9 - 4.9
- 5 - 5.9
- 6 - 37



Data sources:
DEM: CDED slope 1:50,000
Pluton: After Sask Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

2 km

J D MOLLARD

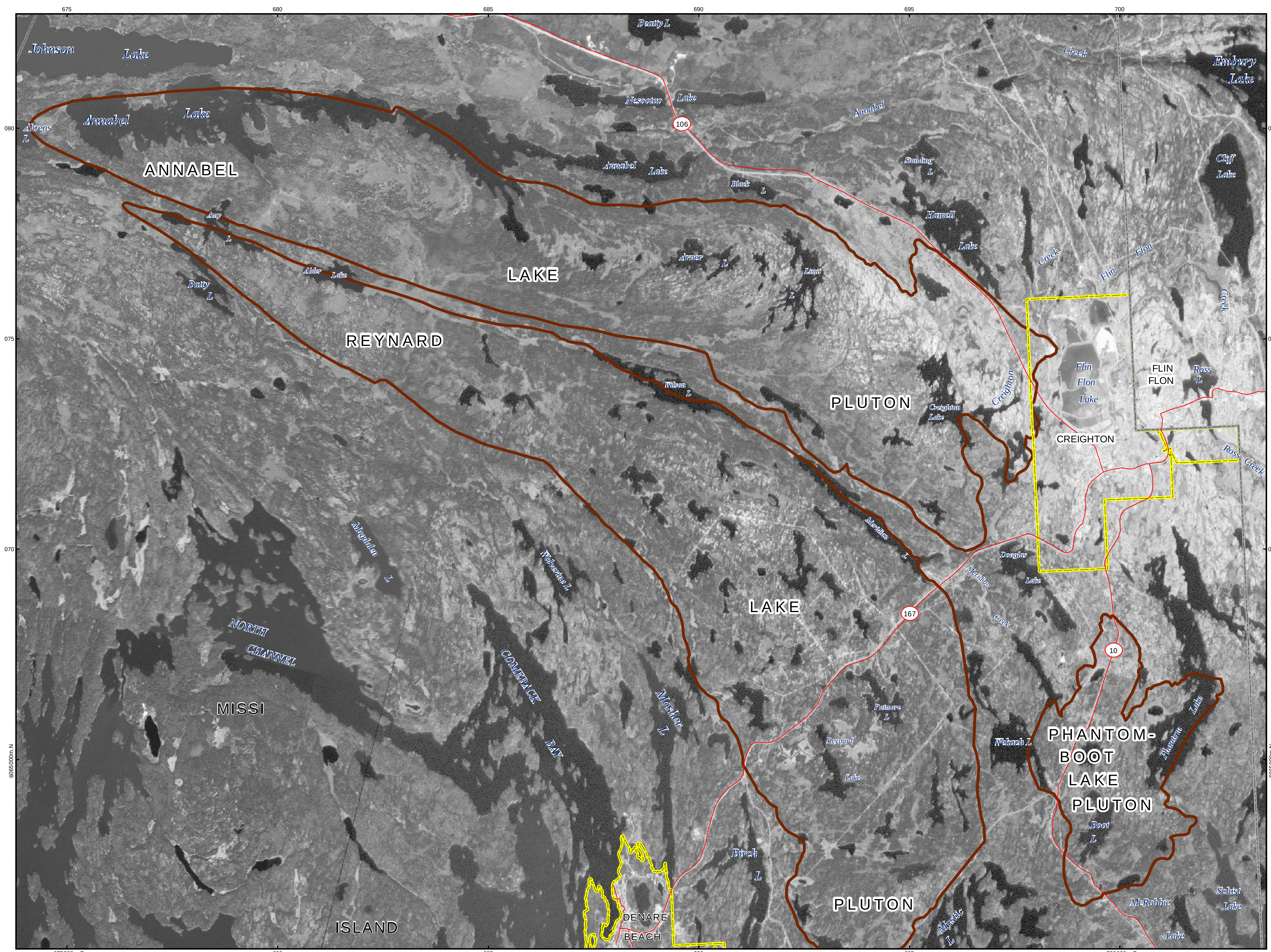
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE

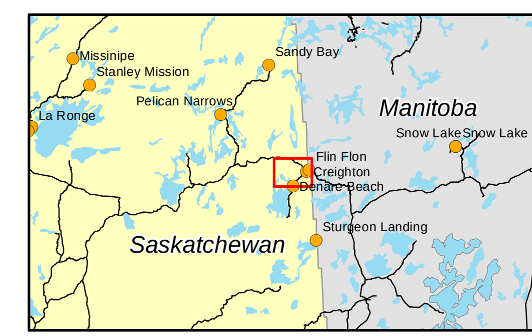
CDED digital elevation data

DESIGN	DVZ	06 JUL 2012	FIGURE 5	REVISION 3
GIS	DSM	08 AUG 2013		UTM ZONE 13
CHECK	JIC	08 AUG 2013		NAD 1983
REVIEW	GS	08 AUG 2013		1:100,000



LEGEND

- Main road
- Provincial border
- Urban municipality
- Pluton



Data sources:
SPOT: Geobase (02 Sep 2006 image)
Pluton: After Sask Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

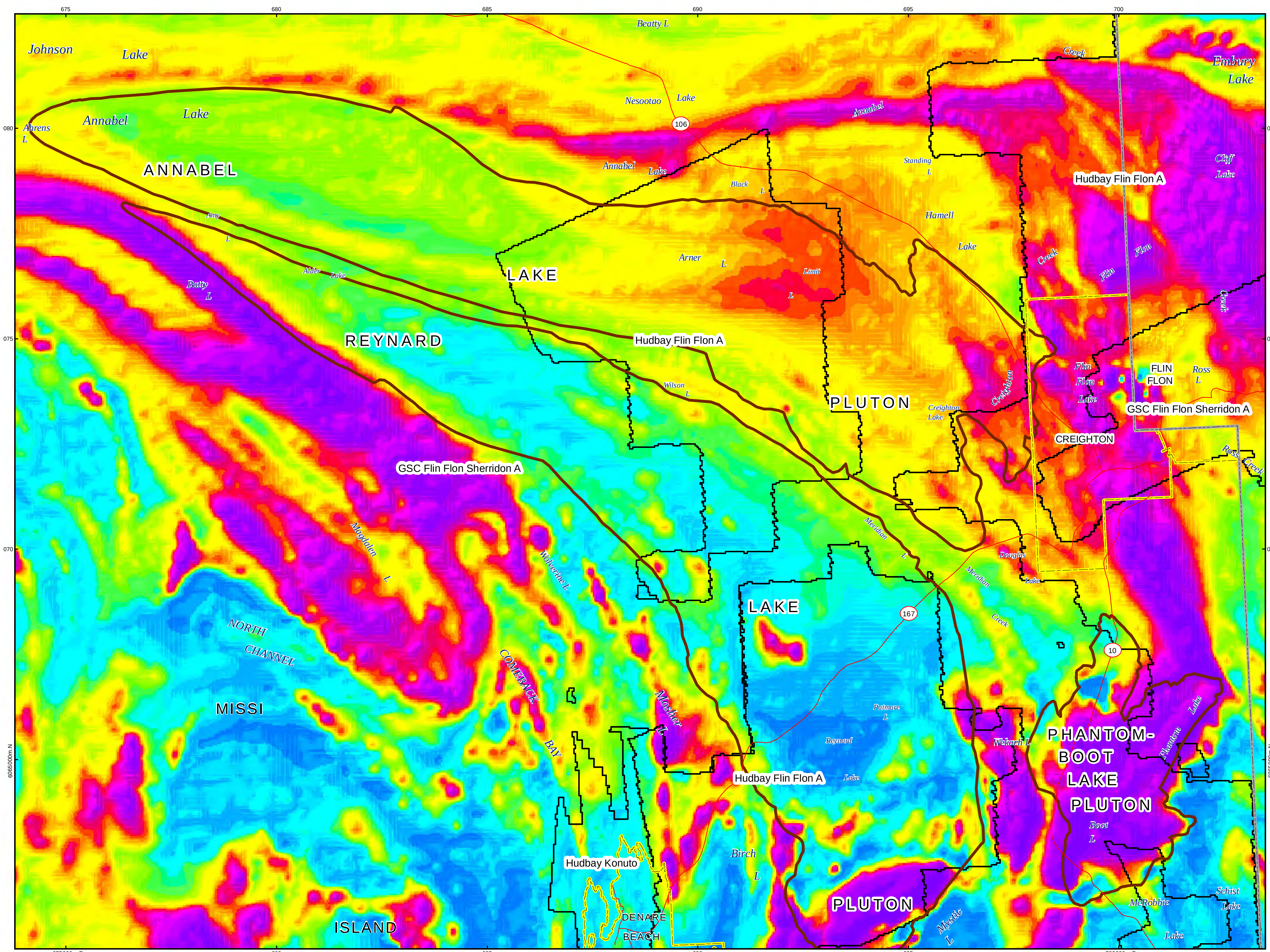
NORTH
2 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
SPOT satellite data

DESIGN	DVZ	06 JUL 2012	FIGURE 6	REVISION 3
GIS	DSM	08 AUG 2013		UTM ZONE 13
CHECK	JIC	08 AUG 2013		NAD 1983
REVIEW	GS	08 AUG 2013		1:100,000

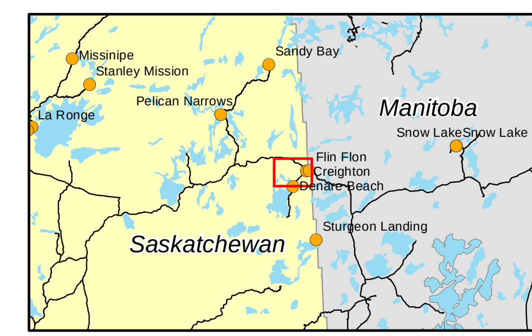


LEGEND

- Main road
- Provincial border
- Urban municipality
- Pluton
- Creighton geophysical survey outlines

RTP (nT)

- 841 - 5,303
- 471 - 840
- 321 - 470
- 231 - 320
- 191 - 230
- 151 - 190
- 131 - 150
- 101 - 130
- 81 - 100
- 61 - 80
- 41 - 60
- 31 - 40
- 11 - 30
- 1 - 10
- -19 - 0
- -29 - -20
- -39 - -30
- -49 - -40
- -59 - -50
- -79 - -60
- -89 - -80
- -109 - -90
- -119 - -110
- -139 - -120
- -159 - -140
- -189 - -160
- -229 - -190
- -918 - -230



Data sources:
Aeromagnetic reduced magnetic field: PGW (2012)
Pluton: After Sask Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

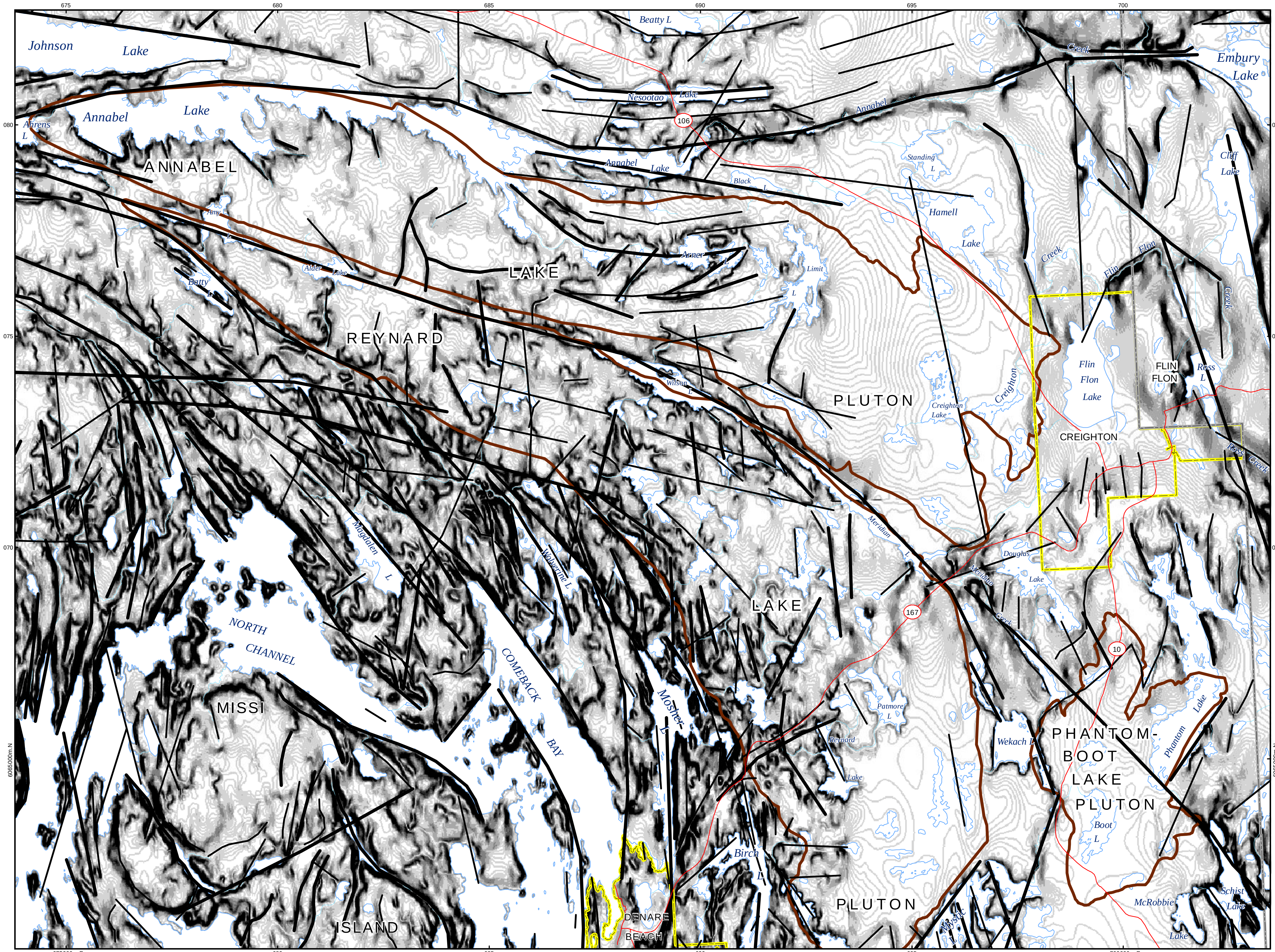
2 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
Pole reduced magnetic field for the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 7	REVISION 3
GIS	DSM	23 AUG 2013		UTM ZONE 13
CHECK	JIC	23 AUG 2013		NAD 1983
REVIEW	GS	23 AUG 2013		1:100,000



LEGEND

Main road

CDED lineament RA_1

1

2

Provincial border

Urban municipality

Pluton

Waterbody

Watercourse

Slope (°)

0 - 0.7

0.8 - 1.8

1.9 - 2.8

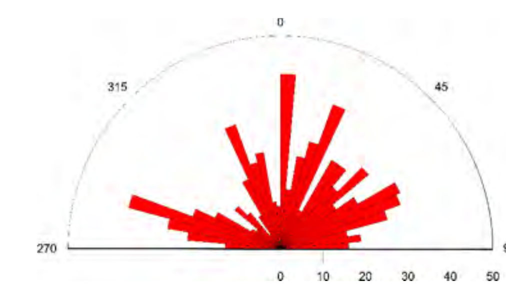
2.9 - 3.8

3.9 - 4.9

5 - 5.9

6 - 37

Creighton CDED Data - Length Weighted Frequency Rose Plot



N = 429

Data sources:
DEM: CDED slope 1:50,000
Pluton: After Sask Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

2 km

J D MOLLARD

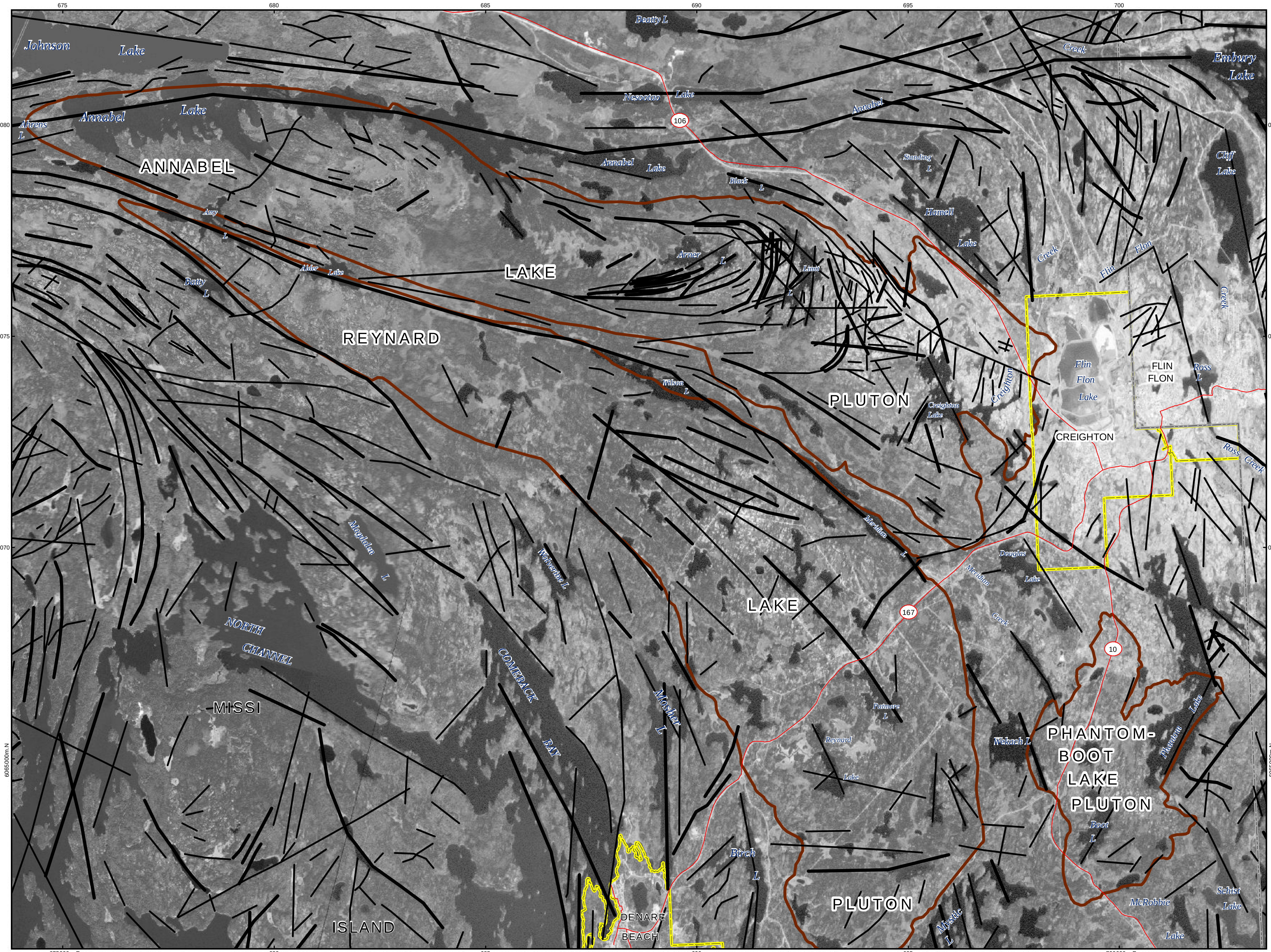
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE

CDED reproducibility assessment (RA_1)

DESIGN	DVZ	06 JUL 2012	FIGURE 8	REVISION 3
GIS	DSM	08 AUG 2013		UTM ZONE 13
CHECK	JIC	08 AUG 2013		NAD 1983
REVIEW	GS	08 AUG 2013		1:100,000



LEGEND

Main road

SPOT lineament RA_1

1

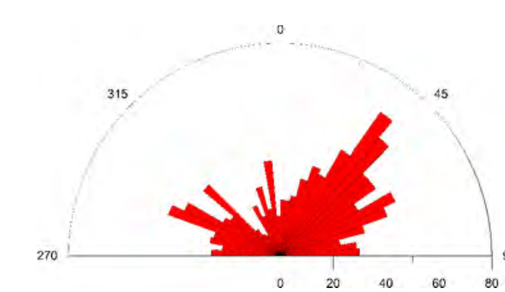
2

Provincial border

Urban municipality

Pluton

Creighton SPOT Data - Length Weighted Frequency Rose Plot



N = 693

Data sources:
SPOT: Geobase (02 Sep 2006 image)
Pluton: After Sask Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

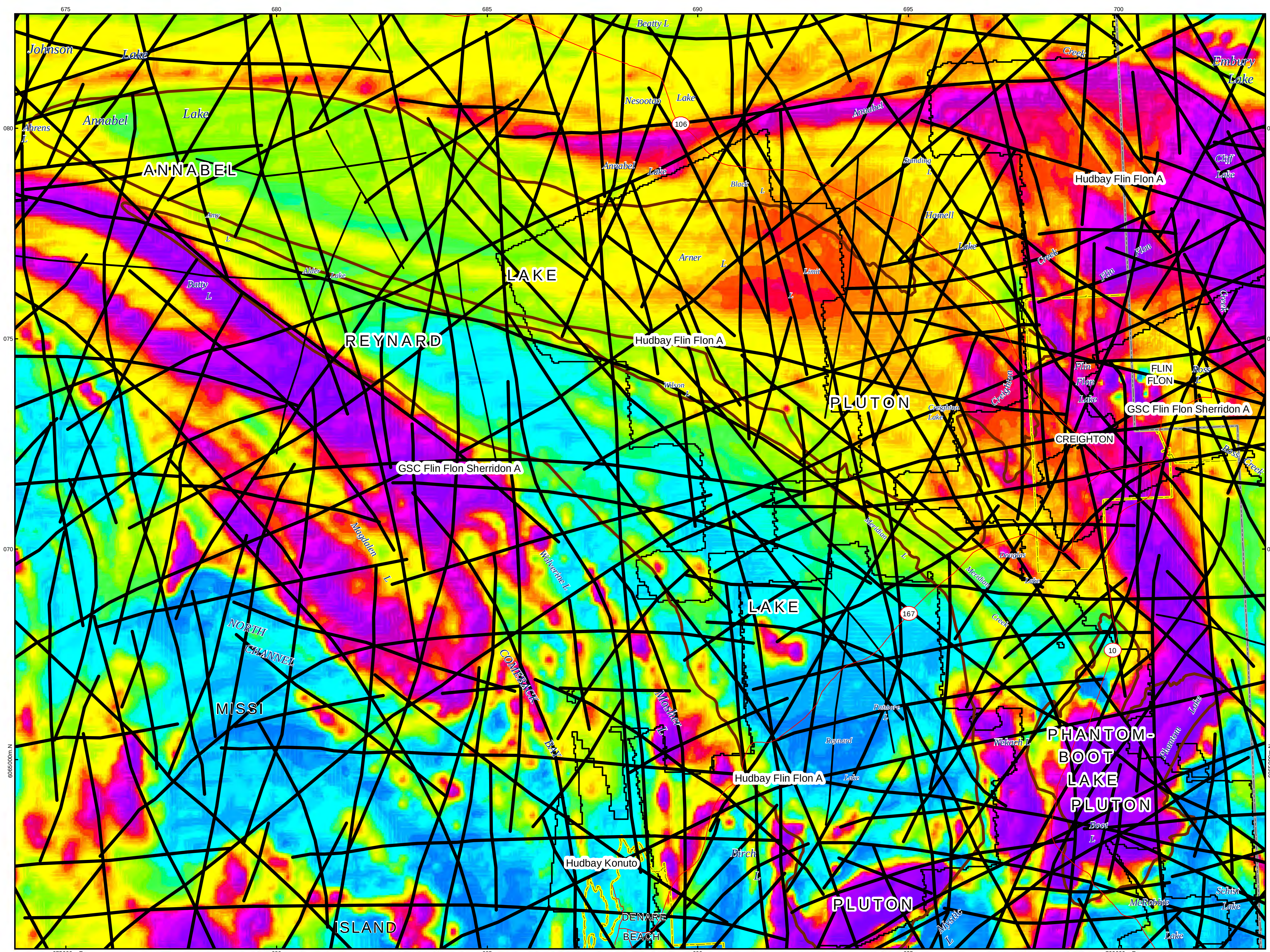
NORTH
2 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
SPOT reproducibility assessment (RA_1)

DESIGN	DVZ	06 JUL 2012	FIGURE 9	REVISION 3
GIS	DSM	08 AUG 2013		UTM ZONE 13
CHECK	JIC	08 AUG 2013		NAD 1983
REVIEW	GS	08 AUG 2013		1:100,000



LEGEND

Main road

Aeromagnetic lineament RA_1

- 1
- 2

Provincial border

Urban municipality

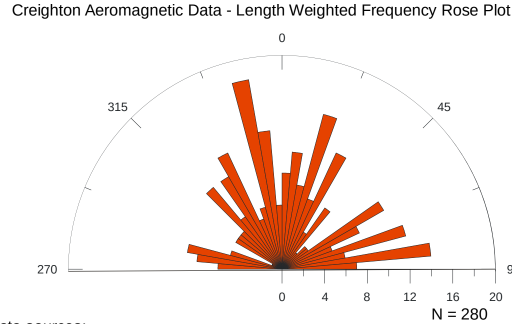
Pluton

Creighton geophysical survey outlines

RTP (nT)

- 841 - 5,303
- 471 - 840
- 321 - 470
- 231 - 320
- 191 - 230
- 151 - 190
- 131 - 150
- 101 - 130
- 81 - 100
- 61 - 80
- 41 - 60
- 31 - 40
- 11 - 30
- 1 - 10
- -19 - 0
- -29 - -20
- -39 - -30
- -49 - -40
- -59 - -50
- -79 - -60
- -89 - -80
- -109 - -90
- -119 - -110
- -139 - -120
- -159 - -140
- -189 - -160
- -229 - -190
- -918 - -230

Creighton Aeromagnetic Data - Length Weighted Frequency Rose Plot



Data sources:
Aeromagnetic reduced magnetic field: PGW (2012)
Pluton: After Sask Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

2 km

J D MOLLARD

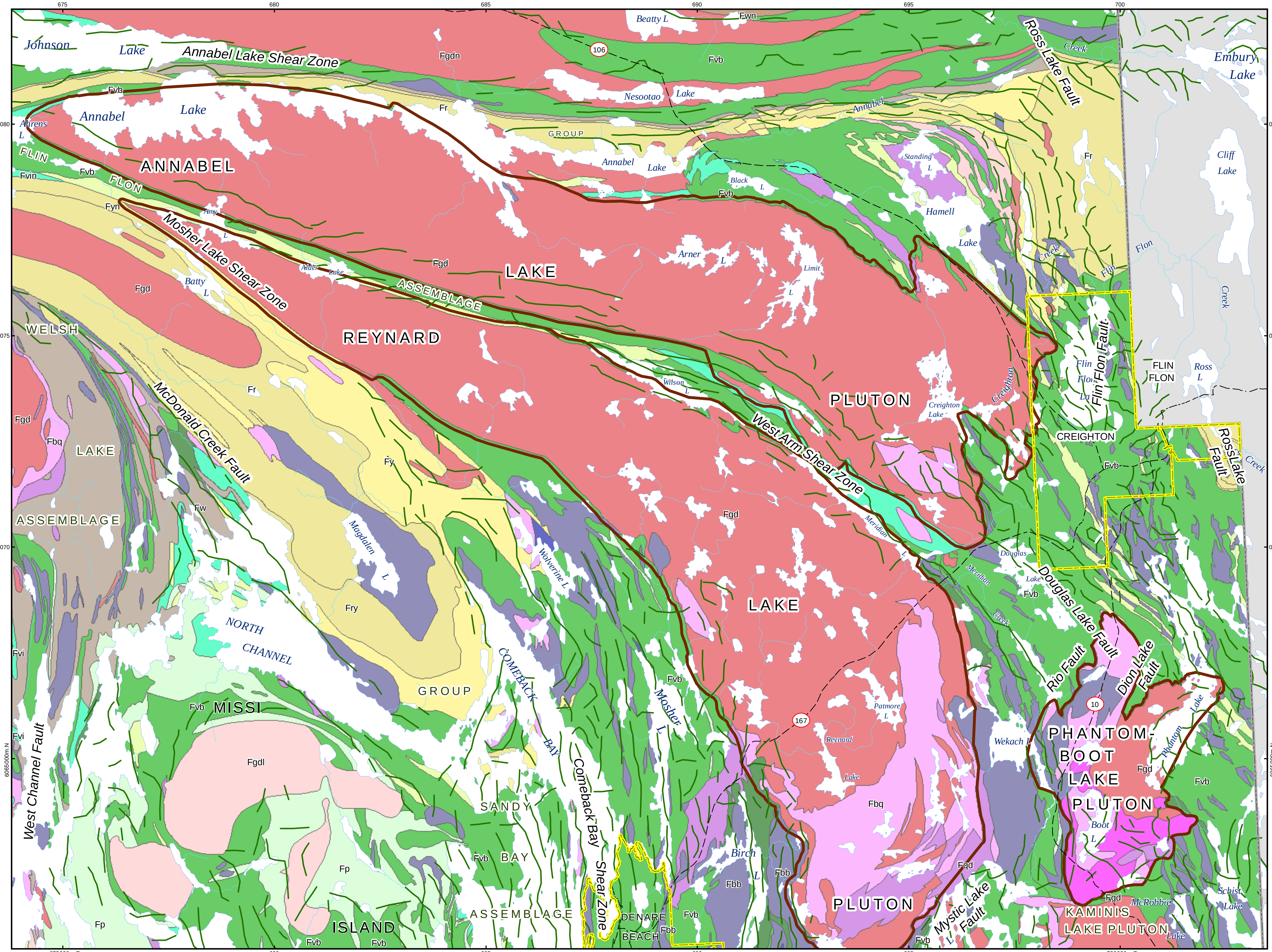
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE

Aeromagnetic reproducibility assessment (RA_1)

DESIGN	DVZ	06 JUL 2012	FIGURE 10	REVISION 3
GIS	DSM	08 AUG 2013		UTM ZONE 13
CHECK	JIC	08 AUG 2013		NAD 1983
REVIEW	GS	08 AUG 2013		1:100,000



LEGEND

- Urban municipality
- Provincial border
- Main road
- Ductile feature
- Pluton
- Waterbody
- Watercourse
- gl - Alaskite-aplogranite
- Fr - Sst, crossbedded sst (Missi Grp)
- Fry - Pebbly sst, pebble cgl, sst. (Missi Grp)
- Fy - Polymictic cgl, sst (Missi Grp)
- Fyn - Cgl gneiss, local psammitic gneiss (Missi Grp)
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

Missi Group

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Mafic protomylonite to mylonite
- Fp - Rhyolite, dacite, porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

Flin Flon Assemblage

Data sources:
Geology: Saskatchewan Geological Atlas (1:250,000)
Ductile feature: mapped by PGW from magnetostratigraphy
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

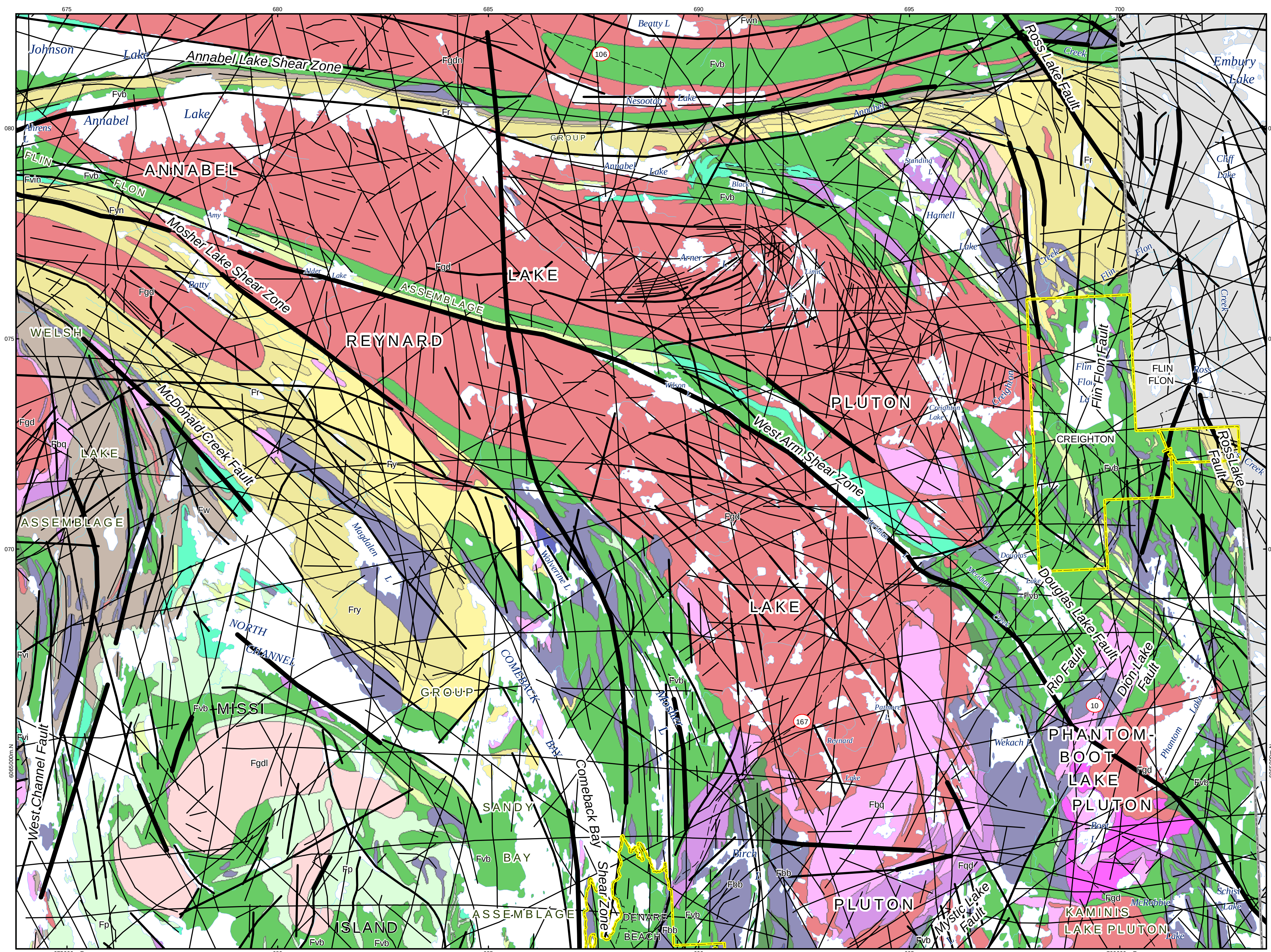
NORTH
2 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT,
LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
Ductile features of the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 11	REVISION 3
GIS	DSM	23 AUG 2013		UTM ZONE 13
CHECK	JIC	23 AUG 2013		NAD 1983
REVIEW	GS	23 AUG 2013		1:100,000



LEGEND

Urban municipality
Provincial border
Main road

Lineament

RA_2

- 1
- 2
- 3

Waterbody
Watercourse

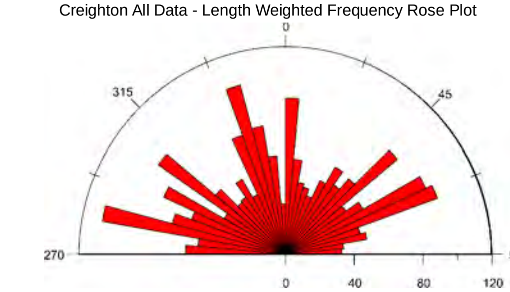
- gl - Alaskite-aplogranite
- Fr - Sst, crossbedded sst (Missi Grp)
- Fry - Pebbly sst, pebble cgl, sst. (Missi Grp)
- Fy - Polymictic cgl, sst (Missi Grp)
- Fyn - Cgl gneiss, local psammitic gneiss (Missi Grp)
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

Missi Group

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Mafic protomylonite to mylonite
- Fp - Rhyolite, dacite, porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

Flin Flon Assemblage

Creighton All Data - Length Weighted Frequency Rose Plot



Data sources:
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

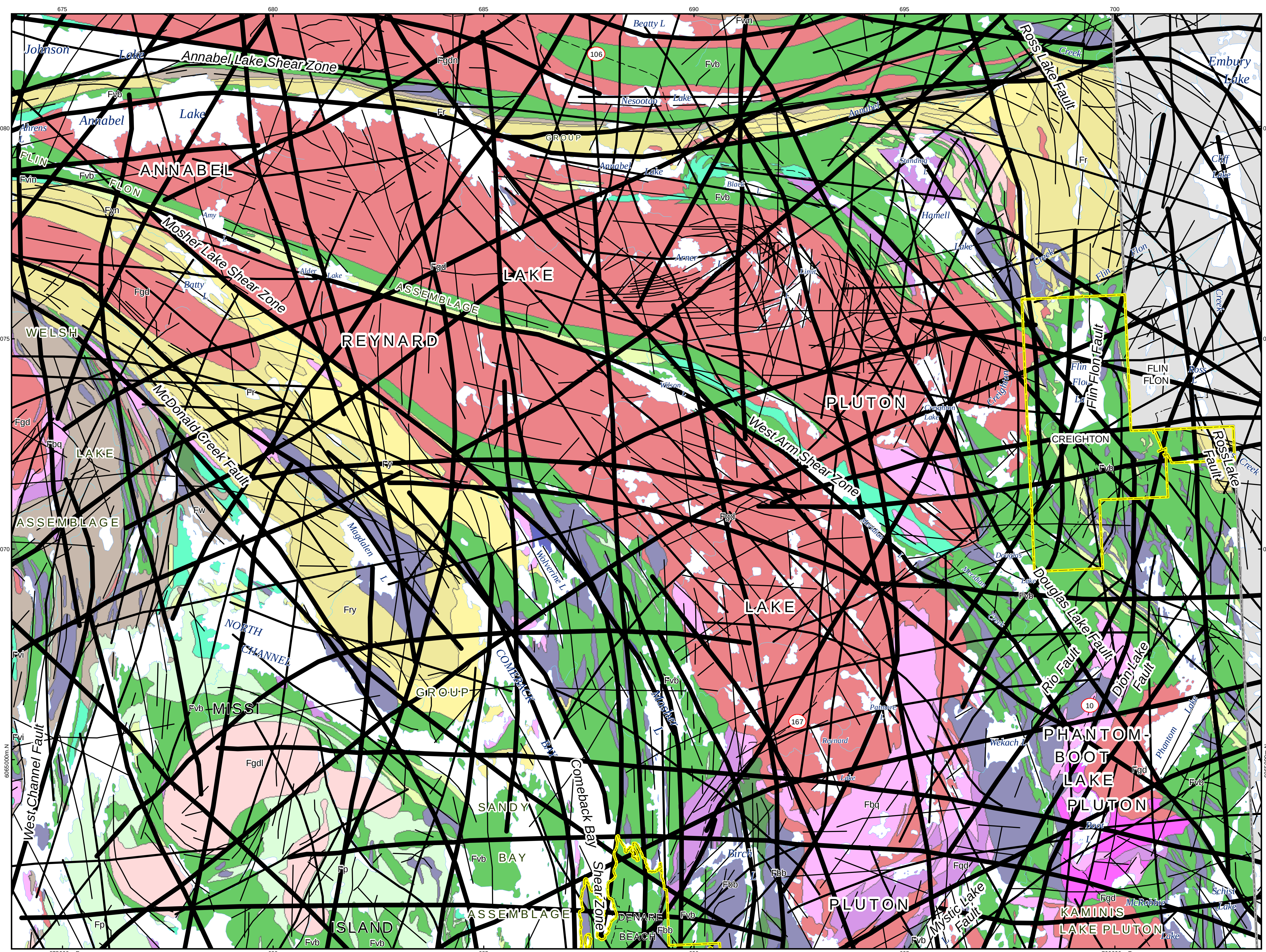
NORTH
2 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
Lineament classification by reproducibility assessment (RA_2)

DESIGN	DVZ	06 JUL 2012	FIGURE 12	REVISION 3
GIS	DSM	23 AUG 2013		UTM ZONE 13
CHECK	JIC	23 AUG 2013		NAD 1983
REVIEW	GS	23 AUG 2013		1:100,000



LEGEND

- Urban municipality
- Provincial border
- Main road

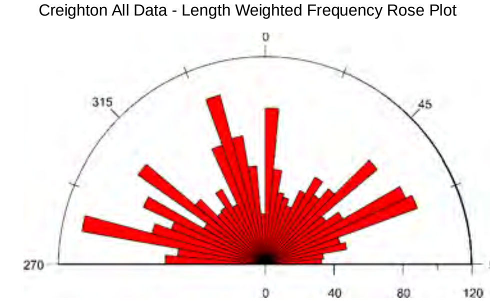
Lineament length

- 0 - 1 km
- 1 - 5 km
- 5 - 10 km
- 10+ km
- Waterbody
- Watercourse
- gl - Alaskite-aplogranite
- Fr - Sst, crossbedded sst (Missi Grp)
- Fry - Pebbly sst, pebble cgl, sst. (Missi Grp)
- Fy - Polymictic cgl, sst (Missi Grp)
- Fyn - Cgl gneiss, local psammitic gneiss (Missi Grp)
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss
- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Mafic protomylonite to mylonite
- Fp - Rhyolite, dacite, porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

Missi Group

Flin Flon Assemblage

Creighton All Data - Length Weighted Frequency Rose Plot



N = 1,107

Data sources:
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

2 km

J D MOLLARD AND ASSOCIATES (2010) LIMITED

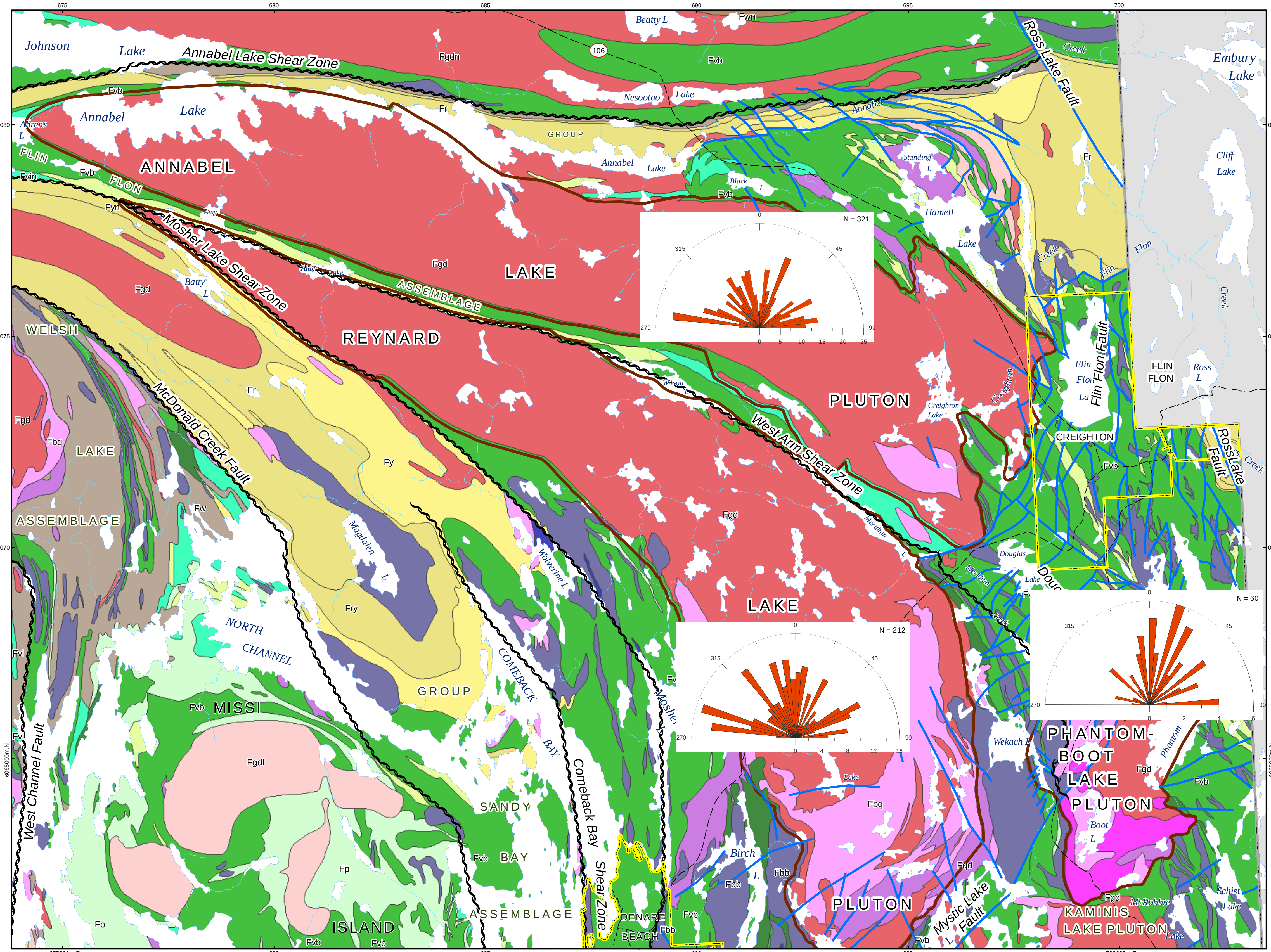
PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE

Lineament classification by length

DESIGN	DVZ	06 JUL 2012	FIGURE 13	REVISION 3
GIS	DSM	23 AUG 2013		UTM ZONE 13
CHECK	JIC	23 AUG 2013		NAD 1983
REVIEW	GS	23 AUG 2013		1:100,000



LEGEND

- Urban municipality
- Provincial border
- Main road
- Mapped shear zone
- Mapped fault
- Pluton
- Waterbody
- Watercourse
- gl - Alaskite-
- Fr - Sst, crossbedded sst (Missi Grp)
- Fry - Pebbly sst, pebble cgl, sst. (Missi Grp)
- Fy - Polymictic cgl, sst (Missi Grp)
- Fyn - Cgl gneiss, local psammitic gneiss (Missi Grp)
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss

Missi Group

- Fgm - Granite-monzogranite-quartz monzonite
- Fgdl - Leucogranodiorite-tonalite
- Fgd - Granodiorite-tonalite
- Fgdn - Foliated to gneissic granodiorite-tonalite
- Fbq - Tonalite-quartz diorite
- Fqd - Quartz diorite-granodiorite-diorite
- Fbb - Gabbro-diorite
- Fu - Ultramafic rock
- Fmx - Mafic protomylonite to mylonite
- Fp - Rhyolite, dacite, porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

Flin Flon Assemblage

Data sources:
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

J D MOLLARD

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, LINEAMENT ANALYSIS, CREIGHTON AREA, SASKATCHEWAN

TITLE
Lineament orientations of plutons in the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 14	REVISION 3
GIS	DSM	23 AUG 2013		UTM ZONE 13
CHECK	JIC	23 AUG 2013		NAD 1983
REVIEW	GS	23 AUG 2013		1:100,000